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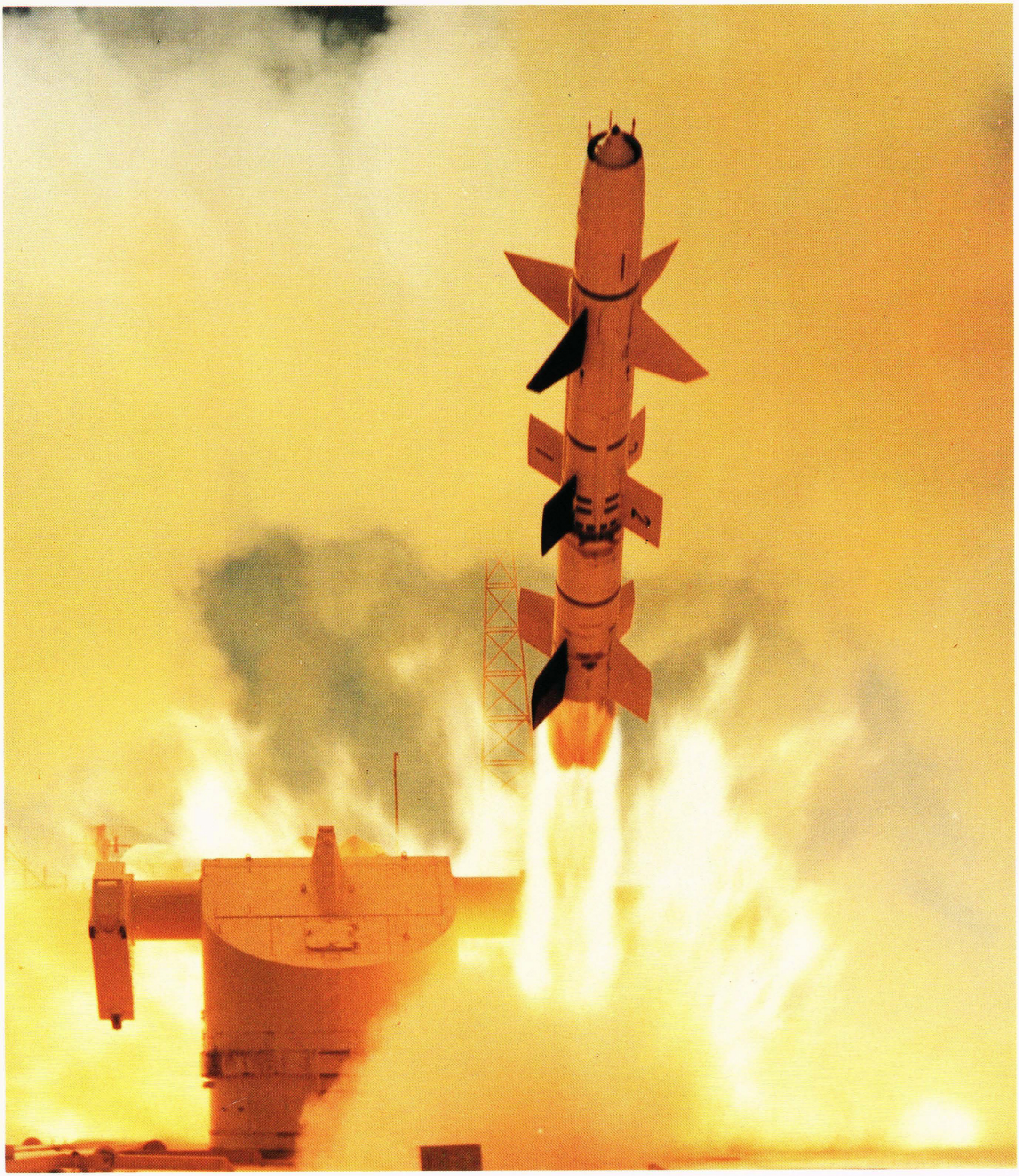

The Talos Missile

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EDITORIAL

APL is recalling this year events that occurred during the four decades after a contract was made between the Office of Scientific Research and Development (OSRD) and The Johns Hopkins University to support and administer a large applied physics laboratory. The contract was signed in March 1942. It was the low ebb in the fortunes of war of the Allied powers. The Laboratory was then almost exclusively engaged in the crash development of a radio-activated proximity fuze for use in the defense of ships against hostile aircraft attacks. In less than a year a working fuze was in production and use. The first assignment to the Laboratory had been accomplished with record speed.

This issue of the *Technical Digest* contains several reflections on that 40-year period. Included is a set of recollections, a "bouquet of reminiscences," by colleagues and friends of Merle A. Tuve (p. 207). Tuve, the founder and first director of the Applied Physics Laboratory, joined the Department of Terrestrial Magnetism of the Carnegie Institution of Washington in the 1920's. He carved out a brilliant career in experimental physics, searching for explanations for the anomalous propagation of radiowaves in the ionosphere and for the forces (then only dimly perceived) within the nuclei of atoms.

Fourteen years later, when the conflict between the United States and the Axis powers became well-nigh inevitable, and the inadequate state of U.S. military preparedness became clear, if only to a few, Tuve gave up his career in basic research and became a key participant in the program of the National Defense Research Council (NDRC). It was set up by Franklin D. Roosevelt in June 1940, and placed under the direction of Vannevar Bush, then the president of the Carnegie Institution of Washington. The aim of NDRC was to bring to bear the insights of physicists and chemists on building up the U.S. war effort. Tuve selected the fuze project, which had been discussed earlier in military circles as a desirable ordnance device but never seriously pursued. He soon showed its feasibility by a convincing field demonstration. Important tasks to provide acceptable reliability and to supervise large-scale production remained to be solved. His Applied Physics Laboratory was the vehicle to bring the project to fruition.

A substantial part of the *Technical Digest* is given over to a description of a subsequent APL undertaking, the development of a Fleet defense missile system that became known as Talos. Much more complex and chancy than the fuze program, it was first seriously thought about early in 1944. It became a formal technical assignment in January 1945, when the outcome of World War II was no longer in doubt. It laid the groundwork for guided missile technologies yet to come. More than ten years went by before the system became operational and part of the Fleet armament.

Talos demonstrated the powers of a dedicated technical team to design and develop a complex mechanical system. Tuve, on the other hand, will be remembered as an individual with consummate skills in his profession, who, in time of need, had the ability to inspire his colleagues to push on into unexplored fields.

President Steven Muller recently summarized his thoughts on the relationship of the Applied Physics Laboratory and The Johns Hopkins University in words that Merle Tuve would have been pleased to hear:*

> If there is a dominant ethos in modern science and modern learning, it is that we are rational. Therefore, as a rational institution that fosters reason, it makes sense to conclude that the use of force to resolve disputes is not rational and that the use of nuclear weapons as part of the employment of force is, in fact, insanity.
>
> But we do not live in a purely rational world. We live in a world that is imperfect spiritually and rationally. In that world, rational analysis must conclude that security and defense are a precondition of peace and the avoidance of force. Because of that, a deep commitment to reason and to peace and an equally deep commitment to national security and national defense are not inconsistent or opposed to each other.
>
> I regard them as twin missions of this institution. I regard them as complementary, and I see in this Laboratory and in this University the mirror image of the problems that face the world and our nation where there is an overwhelming commitment on the part of the most rational and civilized people to peace, and an equally firm commitment, until that day when peace can be assured by other means, to defense and security as the best investment we can make to avoid the use of force.

WALTER G. BERL

*Speech given at the APL 40th Anniversary Dinner for the Principal Professional Staff, March 8, 1982.

GUEST EDITOR'S INTRODUCTION

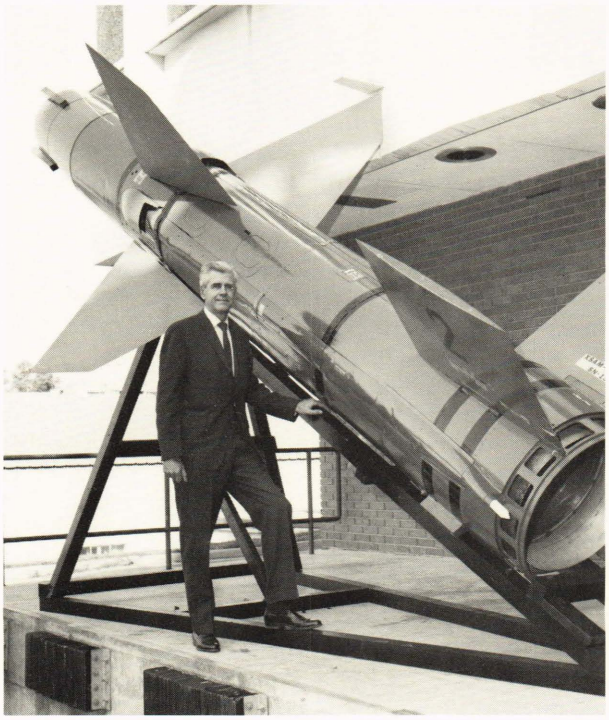
Secretary of Defense Caspar Weinberger said at the launching ceremony of the Aegis ship USS *Ticonderoga* (CG-47), "We are christening the most capable antiair warfare system ever put to sea." Similar words were spoken twenty years earlier at the christening of the Talos cruiser USS *Galveston* (CLG-3). In both instances the statements were true. Though Aegis reflects the technological advancements and refinements of the past decade, it was the broadly based research and development efforts of the Talos program that supplied the underlying technology that gave birth to the present generation of surface-to-air missiles.

The assignment of Task F to APL by the Chief of the Bureau of Ordnance on January 11, 1945, provided the official start of the Bumblebee program, which led to the development and production of the ship-launched Talos, a ramjet-propelled antiaircraft guided missile.

Guided missile technology was virtually nonexistent when the Bumblebee program was begun: supersonic ramjets were not known to have been successfully flown; rockets large enough for boosting a ramjet to flight speed had not been developed; knowledge of supersonic aerodynamics was limited to a few ballistic studies on shells; missile control was limited to airplane autopilot developments; guidance technology, at best, was confined to remote control schemes for low-speed vehicles; and an effective warhead had yet to be invented and developed.

Engineers and scientists were assembled into teams of specific expertise so that an energetic effort could be made on the many problems that such a task presented. Progress in all areas was rapid: test facilities were built and design data were collected; solid-fuel boosters and test vehicles for the 28-inch-diameter ramjet engine were designed, built, and flight tested; supersonic aerodynamics and control technologies were fully developed; beamriding control at supersonic speeds was demonstrated; and the interferometer homing system was invented. By 1951, sufficient information was in hand to formulate general specifications for the Talos prototype missile. In January 1955, the Talos missile was ready for production, and later that year the first missiles were delivered to the Navy.

The following articles describe the development of this first ramjet-powered guided missile, spanning the time from the early concepts to the deployment of a mature guided missile system. Since the Talos missile went through numerous design changes, the first two articles are devoted to the evolution of its development. Six subsequent articles discuss specific technical areas, followed by two sections that are concerned with shipboard placement. The last article summarizes operational lessons learned during the program. It is hoped that these contributions will instill in the reader the excitement felt by the participants in seeking solutions to problems that had not been faced previously.



Roy W. Larson

Guidance and motivation for the preparation of these articles were provided by Mr. Roy Larson. His knowledge of all phases of the program was extensive, and his interest in it was enduring. Outlines and some first drafts had been submitted for his approval when we learned of his sudden death.

The authors were closely associated with Mr. Larson during the development of the Talos missile. It was their desire to proceed with the publication project, not only because they thought the story would be of interest, but to complete the plan initiated by their long-time colleague. It is our hope that this collection of articles is a fulfillment of what Roy had in mind.

FRANK A. DEAN

WILBUR H. GOSS

TALOS IN RETROSPECT

The Talos system, a product of the oldest of the U.S. Navy's antiaircraft guided missile programs, has recently been retired from the Fleet after 22 years of active service. The heavy cruisers for which it was designed as the primary armament have been mothballed or retrofitted with newer systems. USS *Oklahoma City*, with the last Talos missile system on board, was decommissioned in 1980.

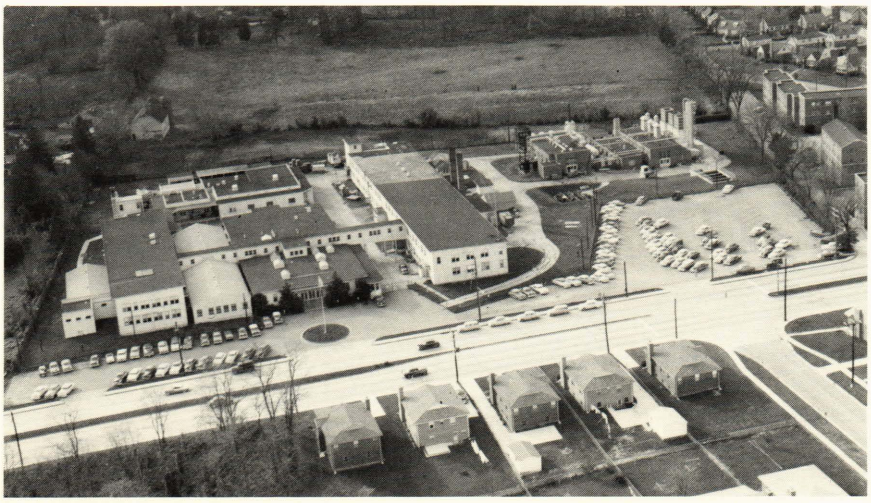
Talos was the largest and most powerful weapon in the Navy's arsenal of antiaircraft missiles. During its years of development, and by successive retrofits during deployment, its range grew from 10 nautical miles to well in excess of 100 nautical miles, with midcourse guidance and a terminal homing system of deadly accuracy. Its capabilities were expanded to intercept ships as well as aircraft; to employ features that made it virtually unjammable; to include a nuclear warhead capable of destroying aircraft flying in formation; and to offer a shore bombardment mode.

At its inception, when controlled supersonic flight was in its infancy and when the concept of guided missile warfare was only just being formulated, the Talos program set out to pioneer, to chart new territory — to do things that had not been done before. Such a pioneering program generates "firsts." It developed the first rocket-launched supersonic ramjet engine, the first interferometric homing guidance, and the first beamriding missile system. It was the first to incorporate a tactical nuclear warhead and the first to develop an explosive warhead capable of ejecting a continuous, expanding steel ring.

The ramjet engine deserves a special comment. Following its extensive development and testing phase, it was manufactured for years without a single production engine ever being test-fired prior to use; conformity to production specifications was the sole acceptance criterion. The engines had to ignite reliably at the instant of separation of the missile from the booster rocket at speeds greater than twice the speed of sound and had to maintain controlled speed throughout flight, while delivering up to 70,000 horsepower. No ramjet engine failed to meet these requirements in more than 750 successive flights.

In the Vietnam conflict, Talos distinguished itself in early engagements by its deadly accuracy at long range. The presence of a Talos cruiser in the Gulf of Tonkin was sufficient to suppress all enemy fighter aircraft flights over the Vietnam coastal strip.

In retrospect, perhaps the most important aspect of the Talos effort was not the missile system itself, in spite of its achievements, but rather what developed from it: the current and future generations of antiaircraft missile systems — both hardware and concepts — and a technology that is now making contributions in fields ranging from satellite systems to biomedical engineering.



Aerial view, in the early 1950's, of APL's Forest Grove Station on Georgia Ave., Silver Spring, Md. The Burner Lab, behind the large parking lot at right, was the site of early ramjet research, development, and testing, which culminated in the Fleet's operational Talos missiles. Midnight explosions and other earshattering sounds emanating from this facility led ultimately to the choice of the rural setting of the present facilities in Howard County, Md.

WILLIAM GARTEN, JR. and FRANK A. DEAN

EVOLUTION OF THE TALOS MISSILE

In 1945, the Bumblebee Program began work directed toward determining the feasibility of building a supersonic guided missile. It was to be ramjet propelled and guided by radar. Because the state of the required technology was then very limited, many problems needed solutions. This article is an overview of the work done to bring the Talos missile into the Navy's arsenal.

At the beginning of World War II, the principal threat to Allied surface ships was from dive-bombing or torpedo-carrying aircraft, with speeds on the order of 250 knots. The airplanes had to make a long, slow, straight-in approach rather close to the target in order to deliver their weapons. This put them in positions where antiaircraft gunfire was quite effective and attrition rates were high.

With the advent of proximity-fuzed antiaircraft shells in 1943, enemy planes were even less able to mount conventional attacks without incurring unacceptable losses. However, it was foreseeable that this advantage of defense over attack would not long continue. As high-performance turbojet and rocket engines became available, and with the advent of radio-guided bombs, it was evident that small, high-speed, air-launched missiles might become a threat to ships whose antiaircraft shells had insufficient range to prevent enemy airplanes from launching such missiles.

A solution to this dilemma was to provide ships with defensive weapons of such range, accuracy, and speed that attacking airplanes would be unable to approach near enough to launch antiship missiles. In the fall of 1944, responding to an inquiry by the Bureau of Ordnance (BuOrd) regarding the feasibility and time scale of such a development, APL proposed a program for a supersonic, radar-guided, ramjet-propelled missile, launched by a solid propellant booster rocket and carrying a payload of about 600 pounds of explosives. It was suggested that, in a period of two to three years and with an expenditure of 10 to 20 million dollars, an initial version of such a "chaser missile" could be produced or, conversely, that proof could be provided that such devices could not be built. It was also proposed that such a development should be sharply focused on the specific objective of developing a supersonic guided missile and be carried out by a closely integrated team responsible for the solution of the overall problem. The anticipated time scale foresaw limited military use in the latter stages of World War II.

In December 1944, the Chief of Naval Operations, Admiral E. J. King, directed BuOrd to proceed with the development of such a missile on an urgent basis. The other Navy bureaus were to give all possible support and assistance.

On January 11, 1945, Admiral G. F. Hussey, Jr., the Chief of BuOrd, assigned the following task to the Applied Physics Laboratory:

> Task "F" — A comprehensive research and development program shall be undertaken, embracing all technical activities necessary to the development of one or more types of rocket-launched, jet-propelled, guided, antiaircraft missiles. The desired performance characteristics are to be defined in consultation with the Bureau of Ordnance as the work progresses, in accordance with the objective of obtaining a weapon of useful military characteristics in the shortest feasible time.
>
> This program shall include pertinent basic research, investigations and experiments, and the design, fabrication and testing of such missiles, their component parts, and supplementary equipment. Alternative modes of promising technical approach are to be pressed either singly or simultaneously, as deemed most effective for the rapid development of a useful weapon. The work shall include cooperation and joint activity, as may be feasible, with those groups in the Armed Services and other agencies which are actively concerned with the development, testing, production and use of similar or related missiles for the United States Government. The work also may include, on request of the Bureau of Ordnance, supervision and guidance of the technical work under other Navy contracts which may be assigned work related to this Task.
>
> The Bureau of Ordnance does not expect by this request and in the immediate future to obtain an ideal or

ultimate antiaircraft weapon, and is aware that the actual results of these efforts cannot be guaranteed or accurately predicted. The Bureau believes, nevertheless, that an immediate attack must be made on this problem, and expects that this will result at the best in the production of an advanced antiaircraft weapon which may be available in the latter stages of this war, and at the least in considerable valuable progress in research and development on jet propulsion techniques, self-guided techniques, and other technical matters of great importance to the future of ordnance.

This was the beginning of the "Bumblebee" program, the development of the technology necessary to build a supersonic surface-to-air guided missile. The key problems were the development of a ramjet engine, supersonic maneuvering, a guidance system that directed the missile to the vicinity of the target, and a warhead that would explode at the appropriate instant.

The program consisted of a family of direct Navy contracts with universities and industry under the integrating technical direction of APL. Initially, industry and APL collaborated in the R&D effort. With the passage of time, industry's role changed from co-developer to that of missile contractor. Bendix Aviation Corp., Mishawaka, Ind., assumed this role for the Talos missile. To maintain the continuity between R&D and production, the engineering program at Bendix was under the technical direction of APL.

INITIAL GOALS

Initial goals were to intercept an airplane target at a horizontal range of 10 nautical miles and 30,000 feet altitude and with a shooting accuracy of 2 mils (2 feet per 1000 feet of target range). Large warhead weights (300 to 600 pounds) were required to achieve kill probabilities of 0.3 to 0.6. This, in turn, meant that a large and fast guided missile was needed to deliver such warheads effectively. Subsonic turbojets were too slow to achieve such intercepts with high-speed targets. Rockets had not been developed at that time to reach such distances. The choice of ramjet propulsion was dictated primarily by the required range and the possibility of extending it by minor alterations in missile geometry, as was done later. Powered flight right up to target intercept was the goal.

EARLY BUMBLEBEE MISSILE DEVELOPMENTS

The development of the Bumblebee missile required ground and flight tests with a variety of test vehicles, each designed to investigate or verify the operation of a specific missile subsystem. These were the following: (a) launching test vehicles that evaluated the performance of the large solid-fuel booster rockets; (b) burner test vehicles to study ramjet engine performance; (c) subsonic control test vehicles that tested radar beamriding; (d) supersonic test vehicles (STV) for the study of guidance and control during supersonic flight; and (e) the XPM, a prototype ramjet-propelled guided missile that incorporated all previous developments. The relationships between these developments are shown in Fig. 1.

STV-3 test vehicles, the most complex of the rocket-propelled test vehicles, were launched by a booster rocket and sustained in supersonic speed by a small solid-fuel rocket. As the first successful supersonic beamriding missiles ever to be flown, they were recognized by both the Navy and APL to have potential as a short-range antiaircraft missile if the telemetry section were replaced with a fuze and warhead. APL accepted responsibility for developing a prototype missile from this test vehicle. The missile was named Terrier.

RATIONALE OF THE TALOS DESIGN

Since the small Terrier missile was to cover short-range antiair targets and was expected to be deployed much sooner than the ramjet-propelled version of the Bumblebee missile (to be known as Talos), goals for the large missile were extended. Maximum range was increased to 50 nautical miles or more, and a terminal homing guidance requirement was generated.

As early work on Task F began to develop confidence that a ramjet missile would be successfully developed, an appropriate name for this missile was sought. From Bulfinch's *Age of Fable*, the name Talos was selected. Talos was a demigod who watched over and guarded the island of Crete. He was made of brass and was reputed to fly through the air at such terrific speed that he became red hot. His method of dealing with his enemies was to clasp them tightly to his breast, turning them to cinders at once. Talos was approved as the name for the new ramjet missile by BuOrd and by the Guided Missiles Subcommittee of the Aeronautical Board on January 5, 1948.

Beamriding for midcourse guidance was an obvious choice, based on successful experience in development of the STV-3. Even though the maximum range requirement of Talos precluded the missile from traveling on a direct line-of-sight trajectory from launch to target (because of excessive fuel consumption on such a flight path at low altitude), it was realized that a guidance beam could be programmed in elevation so that a missile riding along its axis could be made to follow a fuel-conserving trajectory. Beamriding also offered the possibility of simultaneously guiding several missiles with a single guidance beam.

Since beamriding guidance could not provide sufficient accuracy for precise intercepts at ranges of 50 to 100 nautical miles, a terminal guidance phase with a semiactive target seeker was envisaged. The interferometer seeker proved to be the most accurate among the surface-to-air missile seekers of the Navy.

Development of the missile along the above lines led to the pilot line production of the First Tactical Talos missile (SAM-N-6b) shown in Fig. 2. This configuration was flown in 1952, and the First Tactical

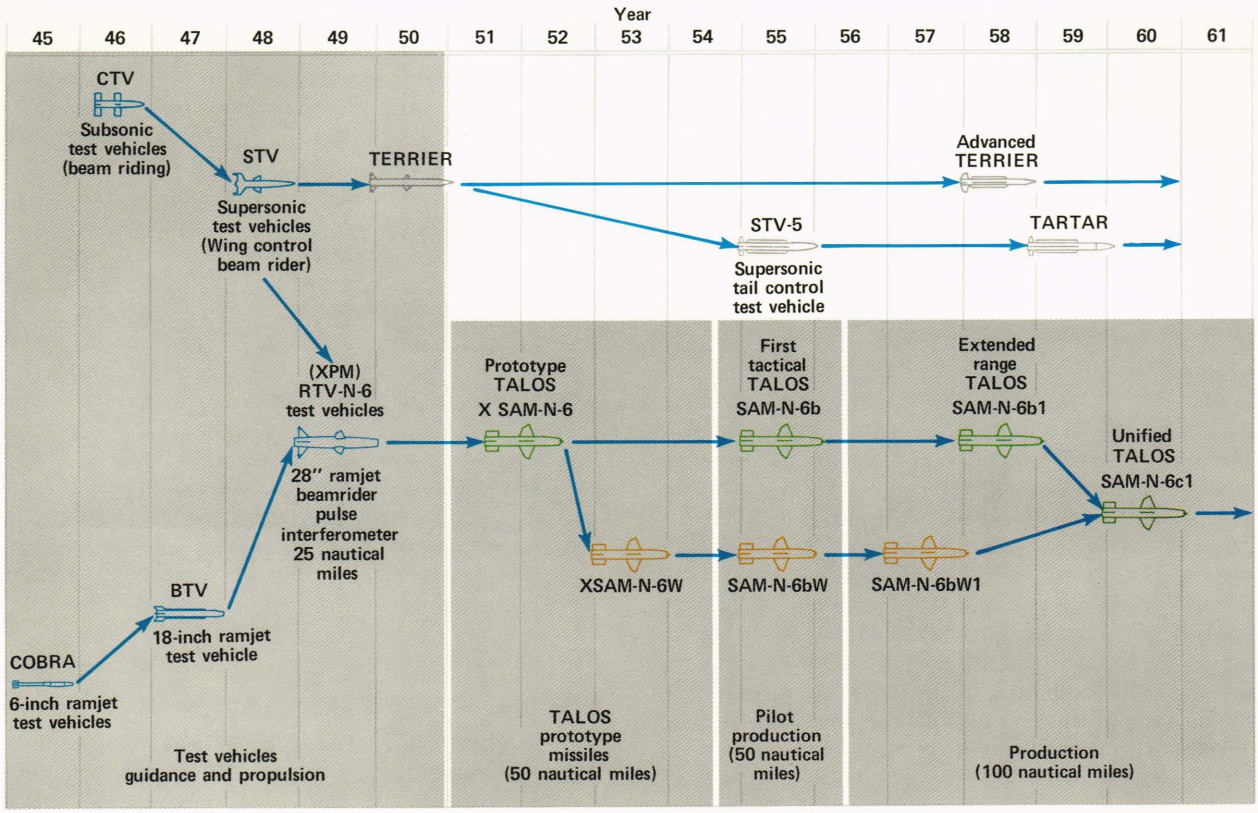


Figure 1 — The evolution of Talos started with the development of Bumblebee test vehicles to investigate operation of missile subsystems and ended with the production of the Unified Talos missile. Bumblebee test vehicles also led to the Terrier and Tartar missile programs.

Talos missile was introduced into the Fleet in May 1958, with the recommissioning of USS *Galveston* (CLG-3). The principal time-determining factor in introducing Talos to the Fleet was ship conversion, a four-year task, following a decision to proceed on a satisfactory missile design.

RATIONALE OF THE TALOS W DESIGN

Analysis of the basic capabilities of the Talos semiactive interferometer homing system included a study of guidance accuracy under conditions where the missile could simultaneously receive microwave energy reflected from two or more aircraft flying in formation. It showed that, for target separations of a few hundred feet, the missile would have a large miss distance. The Talos weapon system was therefore vulnerable to simple tactics that could be used by a well-informed attacker.

A solution to this vulnerability was seen when it became known that a small nuclear bomb was being developed (in 1951) for use by fighter-bomber aircraft. Since this bomb had a smaller diameter than the Talos missile, it was feasible to adapt it as a warhead for Talos.

Talos W, capable of carrying a nuclear warhead, would be guided all the way to the target by the beamrider system used for Talos midcourse guidance. The accuracy of this system at maximum range and the basic need to force large separation distances for attacking aircraft required the kill radius for the warhead to be 1000 to 2000 feet. Estimates of warhead effectiveness showed that gust loading would generally be the kill mechanism at longest range, but that both overpressure and thermal radiation could produce significant effects.

The large value for tolerable miss distance for Talos W translated into a relatively low missile maneuver requirement. As a result of the more forward location of the center of gravity, which increased the missile's dynamic stability, the Talos W maneuver capability was diminished relative to Talos but remained adequate to meet the system requirement.

All aerodynamic surfaces, the combustion chamber, exit nozzle, fuel tank, fuel controls, and the actuators for wing control of Talos W were identical with those of prototype Talos. A modified front end, with an enlarged inner body, was necessary to accommodate the nuclear warhead.

When the Talos W missile development was initiated, it was decided to develop a new beamrider receiver, beacon transponder, and control system electronics. The microwave frequency for the Talos W beamrider and beacon was in the 5 to 6 gigahertz band intended for the tactical Talos weapon system rather than the 9 to 10 gigahertz band then being used in the prototype Talos flight testing. Electronic packaging compatibility between Talos and Talos W was attained in later production missiles.

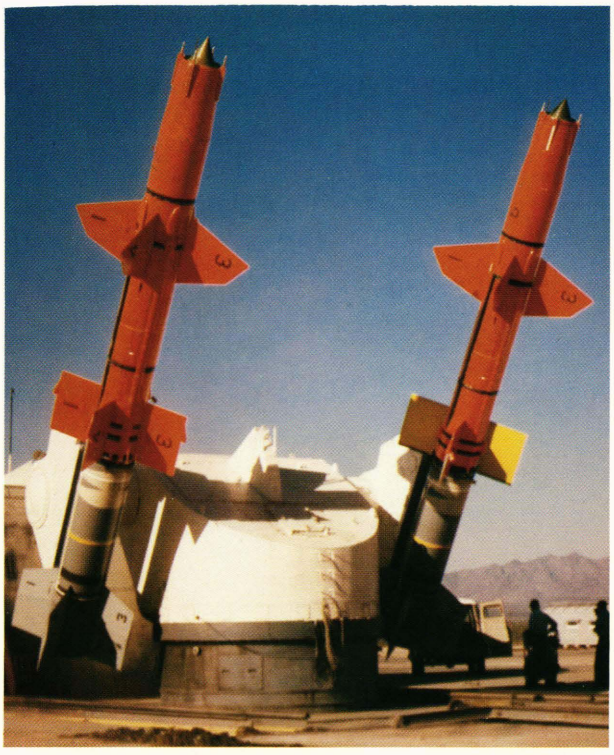


Figure 2 — The First Tactical Talos missiles (SAM-N-6b) are shown on the launcher at White Sands Missile Range. Introduced into the Fleet in May 1958, Talos had a 50-nautical-mile range that employed midcourse beamriding and semiactive pulse homing.

Development along the above lines led to the first successful flight test of a prototype in 1953 (Fig. 3). This was accomplished in 18 months from initiation of hardware design to this first flight. Tactical missile (SAM-N-6bW) production followed the initial 12 prototype missiles. Early in its development, Talos W was seen as a possible new weapon for land defenses and a little later as a possible first anti-ICBM weapon. These possibilities motivated programs to use Talos for the defense of the continental United States.

TALOS CONFIGURATIONS

Capabilities of the missile were enhanced by a succession of configuration variations of Talos (see Fig. 4 and Table 1) beyond First Tactical Talos (identified as SAM-N-6b and SAM-N-6bW). The development program, known as Extended Range Talos (identified as SAM-N-6b1 and SAM-N-6bW1), encompassed a reoptimization of missile flight capabilities for the separate conventional and nuclear versions of Talos. A further development, known as Unified Talos (SAM-N-6c1), took advantage of electronic miniaturization, which made it feasible to package all the electronics of the homing system within the space available for electronics in the nuclear missile. This made it possible to design a single Talos missile configuration for either conventional or nuclear warheads.

Figure 3 — The first Talos W missile was successfully flight tested in December 1953 at White Sands Missile Range.

Extended Range Talos (SAM-N-6b1 and SAM-N-6bW1)

Exploitation of the full-range capability inherent in the ramjet engine was expedited by the interest of the Air Force in the use of Talos for defense of Strategic Air Command bases against rocket-launched missiles. The development of a 100-nautical-mile Talos took place in the 1950's, with the first Fleet firing taking place in 1961.

This development began in 1953 with studies carried out by the missile airframe contractor and APL looking at a possible redesign of the Talos missiles (prototype and W versions) to achieve higher performance. As the analysis proceeded, the improved performance was defined as an increase of the altitude ceiling from 60,000 to 70,000 feet and of the range under optimum conditions from 50 to 100 nautical miles.

The more efficient design of these missiles (greater maneuverability, lower maneuver-induced drag, and greater engine thrust and efficiency) resulted in a higher operating ceiling, the capability to engage faster and more maneuverable targets, and tolerance of greater levels of residual low-frequency angular motion of the guidance beam due to imperfect beam stabilization. Greater missile speed was a factor in obtaining this increase in efficiency and also a decrease in the weapon system tie-up time for any one engagement, with an increase in weapon system firepower.

Modifications to achieve the improved performance were:

1. Increased flight speed at high altitude from 2000 to 2400 feet per second;
2. Increased missile tail fin span and increased speed, providing greater maneuverability, high-

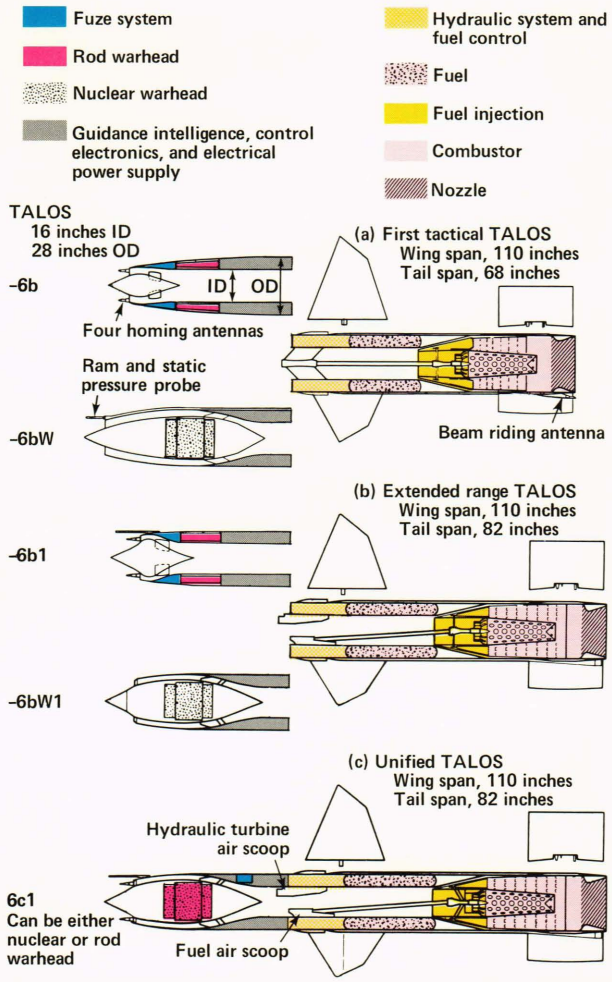


Figure 4 — The Talos configurations can be divided into three classifications: First Tactical Talos, Extended Range Talos, and Unified Talos. (a) The First Tactical Talos employed beamrider midcourse guidance and semiactive pulse homing for terminal guidance. The warhead was annular and surrounded the diffuser. The nuclear version required a special front end. (b) The Extended Range Talos was achieved by enlarging the fuel tank, redesigning the combustor, and improving the aerodynamic efficiency. Air turbine scoops for the fuel and hydraulic systems were placed on the wall of the diffuser. Separate warhead sections were required. (c) The Unified Talos configuration was basically the nuclear version of the Extended Range Talos with a solid-state continuous wave seeker added. The inner body normally contained a rod warhead, but it could also accommodate a nuclear warhead. All subsequent versions of Talos were obtained by exchanging subsystem modules on the basic configuration.

er lift-to-drag ratio, and more linear aerodynamic characteristics;

3. Lengthened fuel tank, providing about 20% more fuel capacity;
4. Six-inch lengthening of the combustion chamber, giving greater combustion efficiency at high altitudes;
5. Double-cone engine inlet, resulting in greater thrust margins at high altitudes;
6. A more powerful booster, providing adequate launch speed for these heavier missiles.

Unified Talos (SAM-N-6c1)

Still unsolved at this stage of development were two problems that forced the next development step. Low-altitude target intercepts were precluded because of excessive sea clutter. Also, the use of two missile types (carrying either nuclear or high-explosive warheads) posed logistic problems and required a determination of the number of each type to be allocated to a ship. In a nonnuclear war situation, vital stowage would be taken up by missiles that would never be launched.

The solution to this dilemma lay in providing interchangeable warheads so that any missile aboard ship could be equipped at will with either a high-explosive or a nuclear warhead. To accomplish this, it was necessary to develop a high-explosive rod warhead to be packaged in the inner-body space occupied by the nuclear warhead and to find space in the SAM-N-6bW1 design for a target seeker and fuze in addition to the beamrider. Fortunately, since a shift from pulse seeker to continuous wave seeker was required to permit low-altitude intercepts, it was possible to meet the space demands simultaneously by developing this new seeker with space-conserving solid-state devices.

Studies carried out in 1956 established the feasibility of adding interferometer homing to the SAM-N-6bW1 missile. This configuration provided the Talos weapon system with missiles that could be used with either a conventional or a nuclear warhead.

The Unified Talos (SAM-N-6c1) was essentially a SAM-N-6bW1 with an alternative, interchangeable, high-explosive warhead and a solid-state continuous wave seeker. The modular construction of this missile provided invaluable versatility. All subsequent versions of the Talos missile were obtained by simply exchanging subsystem modules in this basic SAM-N-6c1 airframe.

Flight testing of the XSAM-N-6c1 configuration began in June 1959. Production of missiles for ship deployment began in the early 1960's.

Talos Antiradiation Missile (RGM-8H)

The need for an antiradiation missile became evident early in the Vietnam conflict, and work was started in 1965 to develop a missile that would passively home on a radar installation. The system and missile requirements were quickly defined and implemented. Successful demonstrations of the system occurred at White Sands Missile Range during 1967, and this was followed by deployment of antiradiation missiles on USS *Long Beach* in 1968.

While specific details of combat applications cannot be released, the radiation-seeking capability was demonstrated by the fact that shore batteries were silenced by missiles fired from ships located in the Gulf of Tonkin. The target discrimination capabilities of Talos also permitted long-range kills of MiG aircraft over land. The long-range intercept capacity limited the enemy air tactics whenever a Talos ship was present. An opportunity to use the surface-to-surface capability did not occur.

Table 1 — Missile designations.

Description	*Designations*	
	Former	*Current* *
Talos prototype, 50-nautical-mile range	XSAM-N-6	None
Talos prototype, 50-nautical-mile range	XSAM-N-6a	None
Nuclear warhead Talos prototype	XSAM-N-6aW	None
First Tactical Talos	SAM-N-6b	RIM-8A
First Tactical Talos W (nuclear)	SAM-N-6bW	RIM-8B
Extended Range Talos, 100-nautical-mile range, modular packaging	SAM-N-6b1	RIM-8C
Extended Range Talos W (nuclear)	SAM-N-6bW1	RIM-8D
Modified RIM-8D, first CW seeker	SAM-N-6b1-CW	RIM-8F
Unified Talos, CW seeker, solid-state electronics and an interchangeable high-explosive or nuclear warhead	SAM-N-6c1	RIM-8E
Antiship capability and guidance improvements		RIM-8G
Antiradiation missile, 120-nautical-mile range		RGM-8H
Unified Talos (final version). Improved seeker, electronic counter-countermeasures, chaff rejection, multiple target discrimination, 130-nautical-mile range (dimer fuel), low-altitude fuzing		RIM-8J

*Missile designations as revised by the Department of Defense in 1963.

THE END OF AN ERA

From the commissioning of USS *Galveston* in May 1958 to the decommissioning of USS *Oklahoma City* in September 1980, Talos missiles protected the Fleet for 22 years. Eventually, the time came to consider their retirement, for several reasons. First, although their one-to-one capability to engage planes at long range was clearly demonstrated and has never been matched, it required the exclusive dedication of a midcourse guidance beam for essentially the full flight time of the missile. This degraded defensive capabilities against multiple azimuth attacks. Second, long-range target identification problems had to be solved before the long-range missile capability was really usable in a congested battle environment. Third, Talos missiles required relatively large launchers and occupied considerable storage space. Fourth, maintenance of the aging Talos ships was expensive. Fifth, new weapon systems using smaller missiles and capable of handling many targets simultaneously had been developed and were available for the threats of the 1980's.

Thus, with the decommissioning of USS *Oklahoma City* the Talos missile deployment came to an end. Yet the technology that was developed and the concepts it engendered continue to exercise an influence over much of modern missilery. Many of the operational missiles in the Fleet today reflect the proud parentage of Talos. We hope they will serve as long and as well.

FRANK A. DEAN

THE UNIFIED TALOS

This article describes the final version of Talos, known as Unified Talos.

The final version of Talos is shown in Fig. 1. Four interchangeable warhead assemblies were available: nuclear, nuclear training, continuous-rod, and exercise warhead with telemetry. The innerbody provided packaging space for the warhead and also acted as part of the annular diffuser for the ramjet engine. Interferometer antennas were placed on the lip of the diffuser inlet. The outer annular region of the forward compartment contained the electronic hardware for the guidance system, behind which were compartments containing the hydraulic power supply and wing control actuators for missile control, batteries for electronic power, and fuel pump and flow regulators for the propulsion system. An 85 gallon fuel tank holding JP-5 or dimer fuel completely encircled the missile and was part of the airframe. Missile speed was regulated by control of the fuel flow.

The electronic equipment was packaged in modules and designed to facilitate checkout and repair. Modules were physically and functionally interchangeable to permit replacement in the event of equipment failure. Interchangeable wings and fins were provided that could quickly be attached to or removed from the missile and booster assembly.

A summary of overall weights and dimensions is given in Table 1.

The missile had four independently movable wings that provided for roll control and steering maneuvers. They were angularly positioned by hydraulically powered actuators through differential-current servo valves. Attitude and roll stabilization were maintained during boost by wing control, assisted by the booster fins. In the midcourse and homing phases, the control system combined outputs from motion-sensing elements with outputs from the missile guidance receiver to provide error signals to steer the missile.

The missile was launched at elevation angles from 25 to 55° (Fig. 2). It was boosted to nominal flight speeds of over 2000 feet per second by a solid-fuel

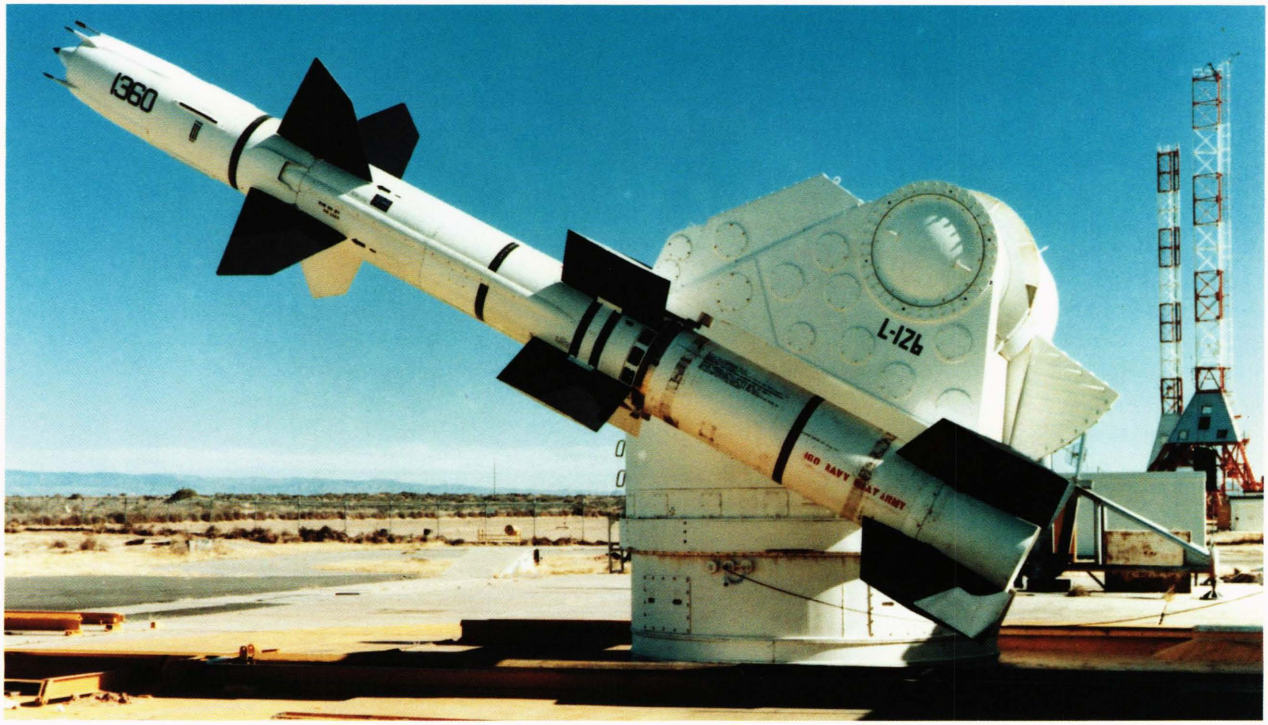


Figure 1 — The Unified Talos is shown in the missile-booster configuration, mounted on the *Desert Ship* launcher at White Sands Missile Range in 1972. This missile could employ either a conventional or a nuclear warhead. Guidance and control modules were physically and functionally interchangeable. The missile was designated RIM-8E. Improved versions of the missile, RIM-8G, RGM-8H, and RIM-8J, were made by substitution of modules.

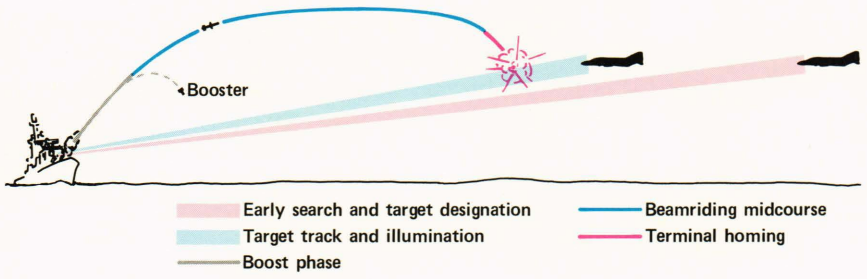


Figure 2 — The operational concept was to launch at elevation angles from 25 to 55°. After the boost phase, the booster rocket was automatically separated from the missile and the ramjet engine was ignited. The missile was then controlled by midcourse beamriding. Near the end of the midcourse phase, the missile was sent a signal that activated the semiactive homing system and armed the warhead.

Table 1 — Unified Talos weights and dimensions.

	Missile	*Booster*
Weight (pounds)	3360	4360
Dimensions (inches)		
Length	254	132
Body diameter	28	30
Wingspan	110	—
Tailspan	82	72

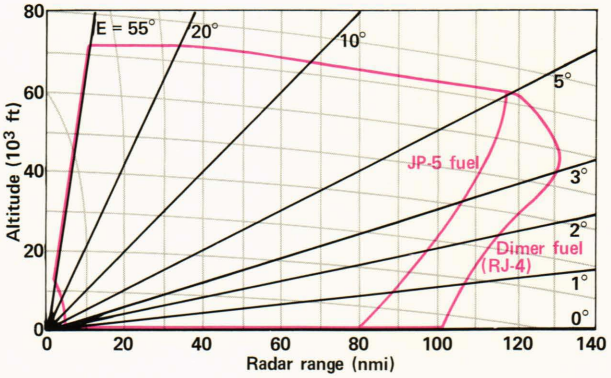


Figure 3 — Kinematic performance envelope for the Unified Talos. The long-range boundaries are determined by fuel exhaustion. The short-range boundary is determined by the time required for boost and 6 seconds of homing. The close-in high-altitude boundary is limited by the maximum climbout angle of 55°.

booster rocket that provided approximately 590,000 pound-seconds impulse for 5 to 6 seconds. After boost, the rocket booster was automatically separated from the missile, the ramjet engine was ignited, and the midcourse flight phase was initiated.

A beamriding system was used during the midcourse phase to steer the missile to a predicted intercept. Near the end of the midcourse flight phase, the missile received a signal that activated the homing system and armed the warhead.

A semiactive continuous-wave interferometer homing system was employed during the terminal phase. Rapid acquisition of the desired target Doppler signal was achieved by a ground-aided acquisition signal derived from the fire control and guidance radars and transmitted via the illuminator beam. The semiactive homing system provided reliable guidance in the presence of sea or land clutter and homed on a jammer at target illumination frequencies in lieu of a target Doppler signal.

An active target-detecting device (proximity fuze) initiated a firing pulse when the missile was within lethal range. Optimum timing of the warhead detonation was calculated using data supplied by the missile homing system.

The intercept envelope was primarily a function of target size, speed, crossing angle, and altitude. The maximum missile-intercept envelope occurred for directly incoming targets (Fig. 3). For small targets at long range, the Talos missile intercept ranges extended beyond the detection capabilities of the ship's radar system.

A fire control channel could engage only one target at a time but could fire a single missile or a two-missile salvo every 46 seconds. That firing rate was considered adequate for long-range targets if short-range targets were covered by other missiles with a higher engagement-rate capability.

Talos had an impressive antiship capability. Its kinetic energy alone extensively damaged any ship it struck, even though there was no warhead. The missile was launched in an antiair mode at a high angle and was programmed to approach the target at a high dive angle. Maximum range capability for that antiship mode depended on the ability of the fire control radar to track and illuminate the surface target.

A surface mode was available for engaging large surface or shore targets. It was designed for firing beamriding missiles on a trajectory that was optimized for a nuclear warhead with command fuzing. The maximum engagement range for a surface target was limited by the guidance radar horizon and the desired altitude of the air burst. Shore targets at distances up to 40 nautical miles were engageable. Flight accuracy when operating against shore targets depended on target position data, set and drift of the ship, ship heading and speed, and ship location. Data on both ship and target position had to be entered into the fire control system by special data transmitters. Several methods were developed for entering those data into the weapon system.

Table 2 — Talos missiles built and flown.

Missile Configuration	*Missile Firings*		*Missiles Built*
	WSMR	*Fleet*	
First Tactical Talos	137	40	229
First Tactical Talos W	60	12	111
Extended Range Talos	57	164	234
Extended Range Talos W	32	56	101
Unified Talos	176	615	1729
Total	462	887	2404

The Talos antiradiation mode made it possible to destroy shore target by homing on radar radiation. Target radiation characteristics, such as frequency and pulse rate, had to be known within certain tolerances to permit target discrimination. Two separate configurations of the homing receiver were required to cover the desired frequency bands. The missile flew a high-altitude trajectory with a maximum range of 120 nautical miles.

A summary of the number of Talos missiles built and flown (not including missiles flown as supersonic targets) is shown in Table 2. The period covers 1955 through 1978, the last record of a Talos flight. The success rate for the missile was greater than 80%. The success rate of the entire system was about 40%.

WILLIAM B. SHIPPEN, WALTER G. BERL, WILLIAM GARTEN, JR., and
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THE TALOS PROPULSION SYSTEM

Development of the ramjet engine for Talos required the solution of many new engineering problems, including maintenance of stable engine operation at high as well as low altitudes; assurance of engine durability during long periods of high-temperature operation; maintenance of stable and efficient intake performance; and provision of a fuel system that would store, pump, distribute, and control the fuel rate.

In January 1945, APL was authorized by the Navy Bureau of Ordnance to commence basic and applied research in support of the development of a guided missile. Until that time, no ramjet-powered flights were known to have taken place, even though the basic idea for the ramjet had been enunciated by René Lorin of France as early as 1913. Intelligence reports of German activities during World War II, and captured documents as well, showed that ramjet engines had been developed for subsonic and supersonic flights, but no applications were made.

The ramjet engine is similar in principle to the turbojet but relies completely on its forward velocity to supply high-pressure air for the combustion chamber. It is not self-starting and requires a rocket booster for acceleration to the minimum operable flight velocity at which it develops sufficient thrust to maintain flight speed or accelerate further. The major components of the ramjet (Fig. 1) are: (a) an air inlet, designed to capture the desired amount of air at supersonic speeds and convert its dynamic pressure to a high static pressure at low velocity for subsonic combustion; (b) a fuel system that provides and controls the fuel flow; (c) a combustion chamber, where heat is added by burning the fuel; and (d) an exit nozzle, where the heated products of combustion are increased in velocity and expanded to ambient pressure.

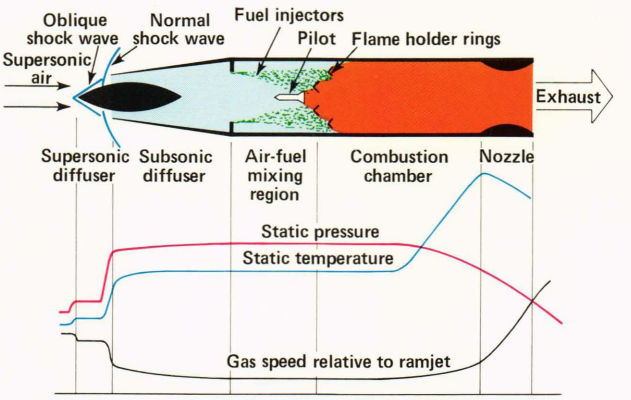

Figure 1 — The ramjet principle is based on increasing the momentum of air passing through the engine. Air enters through a multiple-shock inlet and is converted from supersonic flow at ambient static pressure to subsonic flow at high static pressure. Fuel is mixed with the air, ignited by a pilot flame, and burned in a combustion zone stabilized by flameholders. Energy added to the gases by combustion produces an increase in the momentum of the exhaust. The exhaust momentum and pressure are in equilibrium with internal pressures in the ramjet. Thrust is produced by the vector sum of the forces resulting from pressures on the internal parts of the ramjet.

EARLY HISTORY OF RAMJET DEVELOPMENT

At the start of the program, it was essential to provide laboratory facilities in which ramjets of various sizes could be tested under conditions simulating those expected in flight. Construction of a facility for testing 6-inch-diameter ramjets at the APL Forest Grove Station in Silver Spring, Md., began in February 1945. Plans were made for construction of a full-scale ramjet test facility and supersonic wind tunnel to be located adjacent to the Lone Star Steel Company at Daingerfield, Tex., where large-capacity, high-pressure air blowers were available. The Consolidated Vultee Aircraft Company (CVAC) accepted an associate contract to build and operate this facility, which was later named the Ordnance Aerophysics Laboratory (OAL). Construction of OAL began in June 1945 and was completed in November 1946; testing was initiated in August 1945.

To provide an early indication of the feasibility of ramjet propulsion, a flight test program was started at Island Beach, N.J., utilizing a cluster of high-velocity aircraft rockets (HVAR Model 38) to accelerate 6-inch-diameter ramjet test vehicles to supersonic speed. The first flight tests were conducted on February 16, 1945, to provide data on supersonic drag and to test telemetering performance. The first unambiguous demonstration of ramjet thrust at supersonic speed occurred on June 13, 1945, using carbon disulfide as fuel, less than six months after initiation of the Bumblebee project. The first test demonstrating thrust in excess of drag at supersonic speed occurred in October 1945, using heptane as fuel (Fig. 2). This test vehicle design was modified in early 1946 by in-

THE SUNDAY SUN

BALTIMORE, SUNDAY, JUNE 9, 1946

THE BUMBLEBEE—Here is a model of the Navy's new ram jet engine called "The Bumblebee," taking off from a launching platform (bottom photo). The model in flight (upper photo) is capable of supersonic speeds up to 1,500 miles per hour at high altitudes.

Navy Reveals Supersonic Engine Exceeding 1,400 Miles An Hour

Ram Jet Weighs Only 70 Pounds Has No Moving Parts And Develops 2,000 Horsepower

By WILLIAM J. PERKINSON
[*Sun Staff Correspondent*]

Washington, June 8—The Navy's newest supersonic engine—The Bumblebee—which has hurtled through the air at speeds greater than 1,400 miles per hour was disclosed to the public tonight.

Developing more than 2,000 horsepower, the engine contains no moving parts, and weighs but 70 pounds. Conventional engines capable of producing that much power now weigh more than 2,000 pounds.

The ram jet engine, also known as the "Flying Stovepipe," which has been successfully flown a number of times, is described by the Navy Department as "neither a rocket, missile nor airplane, but simply a vehicle to get through the air at the speed of sound."

Launching Device Secret

Since the ram jet operates inefficiently at low speeds, there must be some way used to bring it up to high speeds. This is done by the use of catapults or rockets. After launching, the engine moves under its own power. Details of the Navy's launching device are still covered by the secrecy of the classified list.

The 600 scientists who are connected with the Bumblebee project faced the same problems as other scientists and engineers trying to perfect an engine capable of driving a plane or missle at supersonic speeds.

The problem is this:

Up to speeds approaching that of sound (743 miles per hour at sea level) scientists do not have to worry about the compressibility of air.

Air behaves like a liquid, thus as in a canoe if you wish to go faster you have to paddle faster and use more energy. But in airplanes and guided missiles, this energy comes from a power plant. The more energy a power plant developed the heavier it had to be.

Builds Up To Barrier

At the speed of sound this compressibility of the air builds up rapidly until it becomes a barrier that is extremely hard to penetrate. More power is needed, and before the advent of the jet engines with their high output for low weight, the problem seemed insurmountable.

Once on the other side of the barrier, in the realm of supersonic speeds, the resistance of the air to passage through it again decreases.

Yet within six months after the problem of producing a supersonic engine was turned over to the Hopkins scientists, the laboratory had successfully flown its first ram jet engine.

Looks Like Stovepipe

"The ram jet looks very much like a stovepipe," Dr. Richard B. Roberts, director of Project Bumblebee disclosed, with openings at both ends.

"It will not operate at speeds below 300 to 500 miles per hour, so we developed a special launching device to get the engine to that speed," he added.

As the engine hurtles through the air, air is scooped into a cone-shaped narrow front opening and compressed by the speed of the jet. This forward portion of the pipe is known as the diffuser. Approximately one third of the length of the pipe is used for diffusing the air, which is mixed with fuel from two injectors.

Wall Of Flame

To the rear of the diffuser is a combustion chamber where a wall of flame increases the momentum of the air as it expands in the diffuser.

This flame front also produces a back pressure which is exerted on the walls of the conical shaped diffuser. The forward thrust of the air on the diffuser's inner walls is what makes the jet engine go. The reaction to this forward thrust is flaming exhaust gases, whose temperatures are above 1,000 degrees Fahrenheit.

Even after it was determined in just what proportion the flame front, fuel inlets and diffusers were to be spaced, other problems arose.

There was the need to record data obtained by actual experiments, and the need to obtain a testing ground.

Must Be Tested In Motion

The ram jets cannot be tested statically, that is on the ground. They must be moved through the air, either in free flight or in a wind tunnel.

But there wasn't time to construct the supersonic wind tunnels necessary. It was decided to test the missiles in flight off Island Beach, N.

At the time the tests were started there was only one supersonic wind tunnel in the country; that was located at Aberdeen Proving Ground. (The Germans are reported to have had 30 such supersonic tunnels.)

The ram jet was first launched "cold"; that is, without the use of its fuel. This was necessary so that scientists could determine the flight characteristics of the engine's carrier. Later the engine was fired, using its own power.

Small Instruments Needed

Since the ram-jet engines being tested were extremely small, it was necessary to develop new means of telemetering information back to the ground. Telemetering is a method by which such data as pressure, temperatures, fuel flows and altitude can be broadcast back to field equipment at the test site.

It was necessary to develop equipment so small and compact that a four-channel radio system, complete with power supplies, measuring instruments and broadcasting equipment, could be contained in a space only slightly larger than a man's two hands.

Here the laboratories' prior work on the proximity fuse, and its close connections with other universities and industrialists paid off.

"Without the components developed for the proximity fuse, the job of relaying the data back to the ground for analysis could not be done," Dr. Roberts said.

Figure 2 — *The Sunday Sun* of Baltimore, reported on June 9, 1946, the development of a supersonic ramjet engine. © 1946, *The Baltimore Sun*. Photo courtesy of World Wide Photos.

creasing the diameter of the forward section to 8.5 inches in order to provide additional packaging space for fuel, fuel metering equipment, instrumentation, and telemetering, as well as to increase the drag to make the unit less likely to accelerate to destruction when operated with fuel-rich fuel-air mixtures. This unit, Model 3B, was named Cobra because of the enlarged front end (Fig. 3).

In late 1945, representatives of Curtiss-Wright, CVAC, and APL met to plan an 18-inch-diameter prototype missile called the Ramjet Test Vehicle (RTV). This RTV was built by the Cornell Aeronautical Laboratory and was first tested at OAL in December 1945. It was designed to carry guidance equipment and a warhead but was unable to withstand the structural stresses of a ground test in a free jet. The only flight test of an RTV used kerosene fuel and produced a maximum acceleration of 2.5 g and a maximum velocity of 2200 feet per second. Further tests of 18-inch-diameter engines were conducted using a similar unit, called the Burner Test Vehicle (BTV), in which the guidance and warhead weight allowance was relocated in a stronger structure.

With the demise of the RTV as a prototype, a larger unit, called the Experimental Prototype Missile (XPM), was designed in late 1946, with a body diameter of 28 inches and a combustion chamber diameter of 24 inches (Fig. 4). The first XPM propulsion test vehicle was flown in March 1949 at the Naval Ordnance Test Station, China Lake, Calif. The predicted thrust was produced, but the engine was extinguished after 7 seconds of operation because improper fuel control caused an excessively fuel-rich mixture. Later flight tests were successful.

The ramjet engine designs, from the 6-inch Model 3B up to the 24-inch XPM, were all basically similar. They had "normal-shock" air inlets that were simple in design and not prone to producing pressure oscillations when the heat release of the combustion chamber or the presence of a tandem booster prevented maximum capture of the inlet air stream. The fuel injectors were simple tubes. The flameholders were combinations of blunt baffles to provide sheltered burning zones and interconnecting "gutters" to spread flame from the more sheltered piloting zones to the main fuel-air stream (Fig. 5). Fuel control progressed from constant fuel flow devices to more sophisticated ones, culminating in the XPM fuel control that throttled the fuel flow within the allowable combustion limits to provide constant-Mach-number flight.

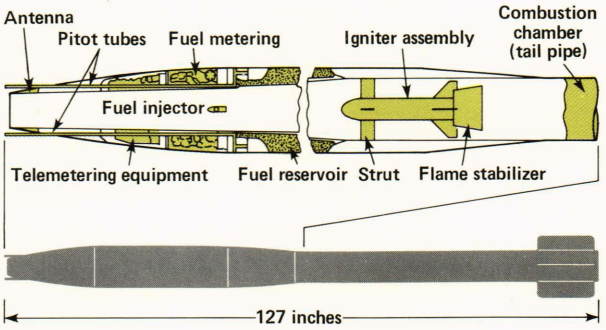

Figure 3 — Cobra ramjet (Model 3B) was the first of a series of test vehicles. Ram pressure was employed to force the fuel out of a flexible neoprene bag into the air duct near the diffuser intake where static pressure was low. The fuel rate was determined by the pressure differential that occurred across a fixed orifice. Ignition of the fuel mixture was by a pyrotechnic flare that burned throughout flight. The tailpipe was made from a stainless steel exhaust pipe from a fighter aircraft. Although the Cobra weighed only 70 pounds, it developed between 2000 and 3000 horsepower — as much as a big bomber engine.

THE TALOS COMBUSTION CHAMBER

High-Altitude Performance

The major problem with early Bumblebee ramjet engines was their inability to provide stable, efficient combustion for long periods at an altitude of 60,000 feet and an airspeed of 2000 feet per second. At these conditions, the combustion chamber had to operate at a pressure of one third atmosphere and at an inlet air temperature of 200°F. To meet this goal, CVAC had initiated tests of a "can"-type flameholder, based on turbojet technology. This development led to a completely different type of flameholding system (Fig. 6) that offered a solution for satisfactory operation at high altitude. Low- and high-altitude tests were conducted on this design in the summer of 1950. The development was successful, and all Talos combustion chambers used this general configuration. The design was unique in its ability to burn efficiently at low air temperatures and pressures. Combustion efficiencies (the ratio of theoretical to actual fuel flow for a given heat release) met or exceeded the ini-

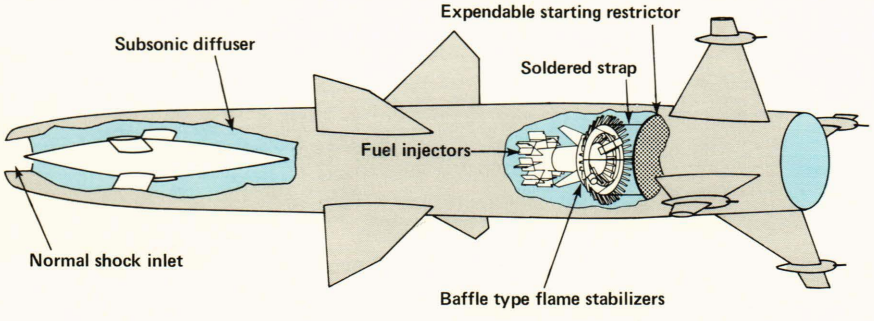

Figure 4 — The XPM ramjet engine required a starting restrictor to permit ignition. This starting restrictor was attached within the combustion chamber with soldered straps to block the duct partially and reduce the flow velocity. On ignition, the solder melted gradually and the restrictor was blown out of the exit.

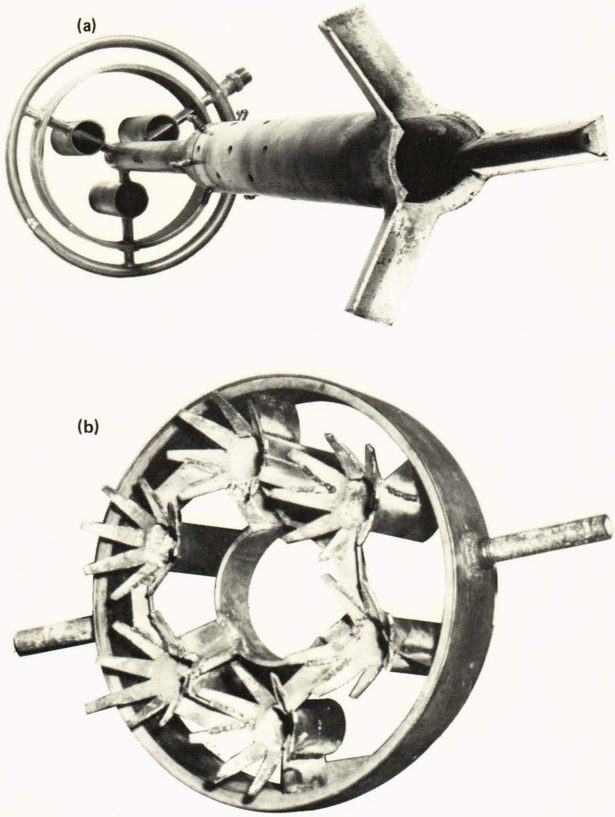

Figure 5 — Flameholder hardware for ramjets in 1946 were combinations of blunt baffles to provide sheltered burning zones and interconnecting gutters to spread flame from sheltered piloting zones to the main fuel-air stream. View (a) shows the fuel injector and radial gutter developed for a 6-inch ramjet. View (b) shows a piloted rake for an 18-inch combustor. The central ring fits into a pilot cone and connects the pilot to the rakes by radial gutters.

tially desired values. This combustion chamber design was frozen on June 1, 1951.

Combustion Chamber and Tailpipe Durability

An ensuing development problem of this combustion chamber design was to improve durability — the ability to maintain the integrity of the sheet metal "can" structure needed for flame stabilization. This problem is placed in perspective when one considers that stoichiometric burning will produce gases at about 3500°F and the melting point of stainless steel is no higher than 2800°F. The solution consisted of providing carefully controlled coatings of zirconia on all surfaces exposed to hot gases to prevent oxidation and to interpose cooling air between the hot combustion products and the metal structures. Persistent burnthrough was located at the intersection of the pilot can and the cooling shroud, where fuel tended to collect in the dead zone. The solution was to operate the pilot as fuel-rich as possible to provide enough fuel in the dead zone for fuel cooling in a local atmosphere too rich to burn. Another durability problem was caused by flow wakes behind fuel system components, which resulted in local reduction of airflow into the cooling shroud and hence degradation of wall cooling. This problem was solved by the installation of small airfoil sections, termed turbulators, to reenergize the boundary layer and the wake. The last of the durability problems was revealed by the first two low-angle shipboard firings of the higher speed Unified Talos (SAM-N-6c1). Both missiles failed because of burnthrough of the combustion chamber wall. The solution was found in increasing metal and zirconia thicknesses, but with a penalty of added weight.

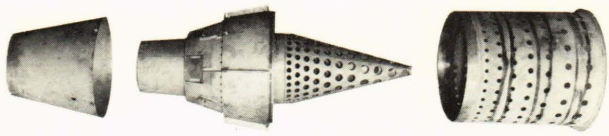

Figure 6 — The can-type flameholder operated with good efficiency at both high and low altitudes. A fuel-air mixture flows through holes in the can wall, and recirculation zones are established behind the holes to act as flame-stabilizing elements.

Combustion Efficiency

A major improvement in combustion efficiency was made for the higher speed and longer range missiles. The higher speed made it possible to reduce the exit nozzle throat diameter and thereby reduce the air velocity within the engine. Six inches were added to the combustion chamber length to improve combustion efficiency for high-altitude cruise. Combustor pressure losses were reduced somewhat by minor redistribution of airflow within the combustion chamber and careful attention to the angle and concentricity of the flow dividers at the combustion chamber entrance.

THE INLET

The function of a ramjet air inlet is to capture the desired airflow and reduce the air velocity from supersonic speeds to values acceptable to the combustion system with the highest practical pressure recovery. Fundamental studies by Oswatitsch in Germany and Kantrowitz and Donaldson in the United States demonstrated both analytically and experimentally what variations of pressure recovery could be expected in supersonic flow, as a function of Mach number, for single shock and multiple external conical shock air inlets. This established the fundamental design requirements for subsequent supersonic diffuser development.

For external multiple shock inlets, the compression is a three-stage process. In the first stage, the airspeed is decelerated to a reduced Mach number in passing through one or more conical shock waves. The second stage is the compression through a normal shock wave near the intake lip to produce subsonic flow. The third stage is the subsonic diffusion of air to produce high pressure at the combustion chamber.

All Talos engines were designed to operate subcritically, that is, at less than maximum air capture (Fig. 7) when the pressure within the combustion chamber

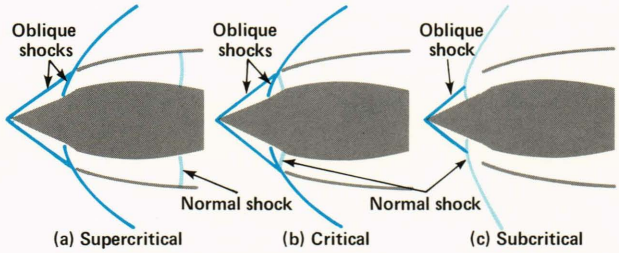

Figure 7 — Modes of diffuser operation are supercritical, critical, and subcritical. (a) Supercritical operation results when the normal shock is downstream from the cowl lip. It occurs at lean fuel/air mixtures. (b) Critical operation occurs when the normal shock is near the cowl lip. This takes place at an intermediate fuel/air mixture and is the most efficient operating point. (c) Subcritical operation results when the normal shock is ahead of the cowl lip. This occurs at rich fuel/air mixtures.

was high, providing maximum engine thrust. Operation in the subcritical regime tends toward instability of the overall diffuser-combustor system, permitting pressure oscillations that cause reduced thrust, missile structure vibration, and extinction of the combustion when operating near the combustion stability limit. Much of the inlet development effort was devoted to establishing the limits of acceptable subcritical operation by wind tunnel tests and overall engine free-jet tests.

Three air inlet designs were implemented before the Unified Talos configuration was established. The initial air inlet for the prototype Talos was a single-cone design, based on National Advisory Committee for Aeronautics (NACA) data that produced significantly better pressure recovery than did a normal shock inlet. During 1953, the entire ramjet system was redesigned for the first tactical missile. The cone angle of the inlet was increased to provide higher supersonic compression. These changes permitted an increase in inlet capture area from 205 to 235 square inches and a decrease in exit nozzle throat size from 70 to 65% of the body area, resulting in an increase in thrust capability. The "W" versions (nuclear warhead capability) of Talos had identical inlet cone shapes forward of the cowl lip but a slightly reduced capture area to compensate for the additional internal pressure loss in the annulus surrounding the larger inner body. In the latter part of 1953, another inlet redesign was needed to accommodate higher operating Mach numbers. A double-cone external compression surface was selected, with a forward cone half-angle of 25° and a second half-angle of 35°. This higher compression angle, combined with higher flight Mach numbers, resulted in a maximum inlet capture area of 360 square inches. The exit nozzle throat size was kept at 65% of the body area.

FUEL SELECTION CRITERIA

Selection of a suitable fuel for a prescribed flight envelope of missile speed and altitude for the ramjet engine depends on optimizing three criteria: (a) the fuel should have favorable thermochemical performance characteristics, expressible in terms of fuel specific impulse; (b) its rates of reaction with air should be such that an uncomplicated combustion chamber can be designed that will provide high combustion efficiency; and (c) fuel handling characteristics and costs should be within reasonable bounds. What weight is to be placed on each criterion depends on the specific engine performance to be achieved. For example, flight range is a very sensitive function of combustion efficiency and favorable thermochemical characteristics of the fuel. If long flight range is desired, criteria (a) and (b) need to be maximized.

The Talos system was designed to begin self-sustained operation at the termination of the solid rocket boost phase and to accelerate to Mach 2.5 during climb to cruise altitude. Long range was to be achieved by flying at altitudes of approximately 60,000 feet. These flight conditions of speed and altitude fixed the temperature/pressure regime for the combustion chamber in which fuel was to be injected, ignited, and burned. The thrust-producing temperature changes in the working fluid were achieved by varying the concentration of fuel in the air streams. At the start of the Talos development program, fuels were selected in which the reaction rate criterion (b) was emphasized at the expense of high thermochemical performance. Proof of principle was achieved with carbon disulfide and propylene oxide, both substantially more reactive than fuels based on carbon and hydrogen (hydrocarbons) alone.

As experience with the design of effective fuel injectors and flame stabilization devices grew, it became possible to turn to hydrocarbon-based fuels that would satisfy criteria (a) and (b) and also meet the operational requirements of reasonable cost and safe handling. By and large, hydrocarbon fuels rank high in all three of the fuel-selection criteria and have, therefore, been used as the preferred fuels. Only boron hydrides (in which boron acts as the hydrogen "carrier") offer substantial improvements in both criteria (a) and (b), with some reduction in criterion (c).

Table 1 summarizes the suitability of fuels that were investigated in the course of the Talos development. Some sulfur- and oxygen-containing fuels offer benefits of ease of ignition and rapid flame propagation but at the expense of thrust per unit weight of fuel. Boron hydrides provide superior kinetic performance and high fuel specific impulses but at the expense of cost and ease of handling. Saturated aliphatic or aromatic hydrocarbons, while somewhat deficient in reactivity, nevertheless perform well when extreme flight ranges are not of vital importance.

As military specifications were developed for jet engine fuels, JP-5 was selected for use in the early production Talos. The value of higher density fuels in providing additional range capability was recognized early in the engine development program, and tests with tetralin were conducted at OAL. A less expensive high-density fuel was methylcyclopentadiene

Table 1 — Suitability of fuels in Talos ramjet engines.

	S_a	S_f	$S_{f,d}$	*Kinetics*	*Toxicity*	*Storage*	*Thermal Stability*	*Viscosity*	*Cost*
Carbon disulfide	P	P	P	E	F	G	G	G	G
Kerosene	G	G	F	F	E	E	E	G	E
Propylene oxide	F	F	F	G	G	F	F	G	F
Methylcyclopentadiene dimer	G	G	G	F	G	F	F	G	F
Kerosene-boron slurries	G	E	G	F	E	F	E	P	F
Methylacetylene	E	G	F	E	G	F	F	G	F
Boron hydrides	E	E	E	E	P	F	P	G	P

P = Poor
F = Fair
G = Good
E = Excellent

S_a = air specific impulse (stream thrust at sonic velocity divided by air mass flow)
S_f = fuel specific impulse (S_a/(fuel/air ratio))
$S_{f,d}$ = density specific impulse ($S_f \times$ density)

dimer, which has 12% higher volumetric heat release than JP-5. The dimer fuel was successfully tested in the first tactical combustor at OAL in 1955. In 1964, when additional range was desired for the Unified Talos, the use of that fuel was reconsidered. However, its storage stability characteristics were unsatisfactory because, as an unsaturated hydrocarbon, it tended to polymerize with time. A program was completed to hydrogenate the dimer to form a stable saturated compound. This fuel was used after 1966.

THE FUEL SYSTEM

The Talos fuel system provided fuel to the combustion chamber to maintain stable combustion and to control engine thrust. For maximum stability of operation, the pilot required fuel at a rate that provided an approximately constant and optimum fuel-to-air ratio. For the main combustor, the fuel rate was varied from zero to a maximum near the overall stoichiometric fuel-to-air ratio to provide the required thrust. Fuel systems for the prototype and First Tactical Talos controlled the fuel flow to maintain constant speed. Since the temperature-sensing units used to control velocity were prone to malfunction, the fuel systems for Extended Range Talos and Unified Talos were designed to control Mach number as a function of altitude.

The fuel controls operated from sea level to 70,000 feet altitude, representing a 17:1 variation in airflow through the engine. They also had to provide fuel for engine ignition within a few tenths of seconds after missile separation from the rocket booster. Fuel had to be injected into the air stream to provide local air-to-fuel ratios that were within the burning limits of the fuel. Other considerations for fuel system design included: (a) high flight accelerations (about 15 g longitudinally during boost and up to about 15 g laterally in flight); (b) accelerations when missile roll-control was established; (c) low combustion chamber pressure at high altitude; (d) vibration and heating during flight; and (e) sudden variations in pressure and airflow at the time of rocket booster separation. Small volume and weight, compatibility with the annular packaging space of the missile, long storage life, reliability, and low cost were additional design considerations.

Figure 8 shows the main elements of the Talos fuel system. The outlet of the annular fuel tank was sealed by a valve controlled by nitrogen pressure. Stored under pressure, nitrogen was released by a valve that was opened by acceleration during boost, pressurizing the fuel bladders inside the fuel tank and opening the fuel tank valve. Fuel flow from the tank was maintained during periods of high missile acceleration by channels within the tank formed of perforated sheet-metal segments. The bladder material had to withstand the stresses generated by fuel motion and the heating by the hot walls of the central air duct.

A centrifugal pump driven by an air turbine was the chief means of moving the fuel to the fuel nozzles. High-pressure air bled from the central air duct provided a suitable energy source for the air turbine. Fuel pump inlet pressure was provided by the nitrogen pressurization.

Separate regulators were used for the pilot and main fuel. A probe ahead of the engine inlet provided freestream pitot and static pressure measurements for the fuel system. These pressures were used to measure flight Mach number, altitude, and engine airflow. The fuel regulators were required to control fuel flow rates over a range of about 20:1 for the pilot burner and more than 100:1 for the main burner.

Main and pilot fuel entered the combustion chamber in concentric pipes. In either case, the fuel was

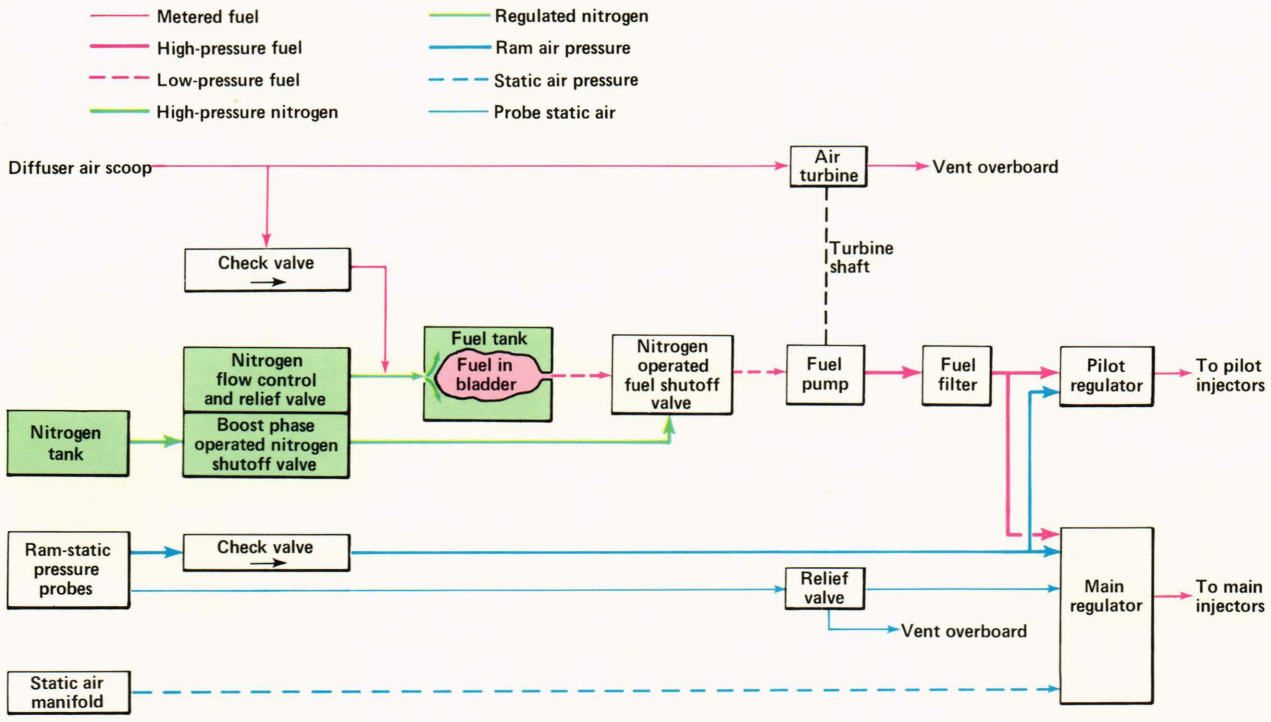

Figure 8 — The Talos ramjet fuel system maintained stable combustion and controlled engine thrust. The fuel tank was normally pressurized with nitrogen, but diffuser pressure was also available as backup. A centrifugal pump driven by an air turbine provided high-pressure fuel to the pilot and main fuel regulators. Ram and static air pressures were used to regulate the fuel flow. The regulator compartment was vented to the atmosphere through louvers and was employed as an atmospheric sump for the regulator.

discharged into the air stream through an annular array of nozzles. The injector system maintained proper fuel distribution during high-g lateral maneuvers and sustained proper fuel flow in the presence of variations in air pressure. Nozzles used in the pilot injector had linear pressure-versus-fuel flow characteristics that assured uniform flow distribution to the pilot. The main fuel injectors used spring-loaded, fixed-pressure nozzles and a fuel distribution valve to maintain uniform fuel distribution to the individual nozzles.

THE UNIFIED TALOS RAMJET PROPULSION SYSTEM

No major changes were made to the ramjet design after the Unified Talos configuration was established. This final design provided reliable and adequate propulsion for all flight conditions that fell within the Talos operating envelope.

The supersonic inlet employed double-cone external compression and was designed for best operation for flight Mach numbers ranging from 2.0 to 2.5. The engine operated subcritically at low Mach number but inlet stability was maintained at maximum engine thrust.

The fuel rate was controlled so that the flight Mach number was regulated between 2.0 and 2.5 depending on the ambient static pressure (which is related to altitude). Dimer or JP-5 fuel could be used with minor adjustments to the fuel regulator. The capacity of the fuel system provided a maximum range of 130 nautical miles with dimer and 115 nautical miles with JP-5.

The final Talos combustor is shown in Fig. 9. The combustor was constructed of conical sections and assembled to provide concentric regions where pilot flame and main air-fuel mixtures are combined to provide stable combustion. Holes in the central cone produced vortex wakes of relatively low speeds (less than the spreading speed of the flame), which provided the flameholding action (Fig. 10). Burnout of the combustor was prevented by proper distribution of the air and fuel and by appropriate zirconia coatings. Ramjet ignition was by a spark plug located in the pilot region. The length of the combustion chamber provided adequate time for efficient combustion. A contracting/expanding exit nozzle was employed to reduce air speed in the combustor and to match the combustor with the inlet.

A summary of Talos ramjet propulsion capabilities is given in Fig. 11. Two independent relations are shown: the maximum acceleration due to thrust, and deceleration due to drag. Horizontal flight and properties of the atmosphere for an NACA Standard Atmosphere are assumed. For a given altitude, the difference between the maximum acceleration from

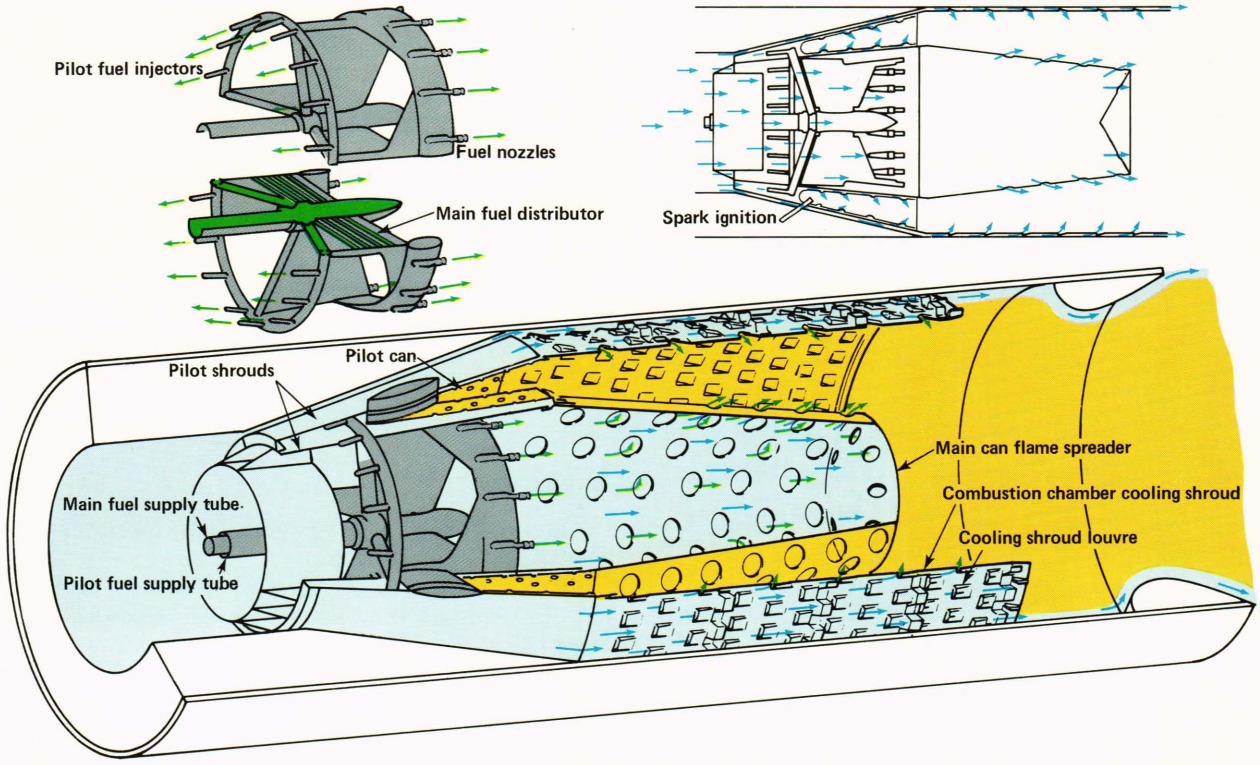

Figure 9 — The Talos combustion chamber design used approximately 20% of the captured inlet air along the outer wall for combustion chamber wall and nozzle cooling. Another 15% of the air passed into a pilot section, where pilot fuel was injected through high-pressure spray nozzles to maintain stable combustion under all conditions of flight. The remainder of the air flowed through the center of the engine to the main flamespreading section, where fuel was injected through low-pressure nozzles and burned to produce the engine thrust. Combustion chamber parts were ceramic-coated to prevent oxidation at high temperatures.

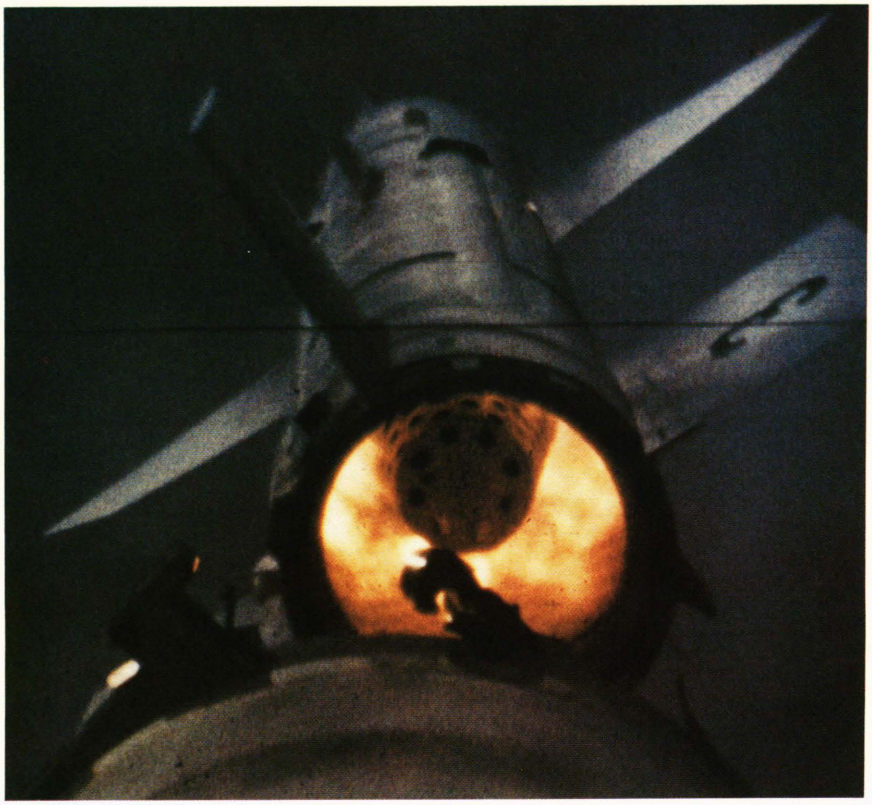

Figure 10 — Flameholding action in the Talos combustion chamber was accomplished by vortex wakes produced by jets from holes in the central cone. Flameholding action during a Talos flight test is shown as viewed from a booster rocket.

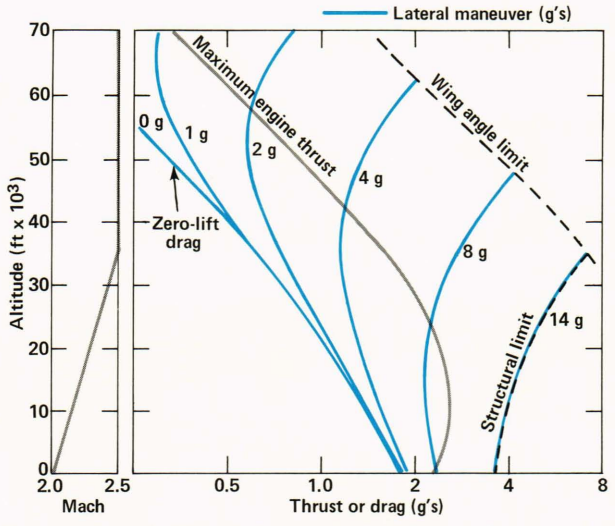

Figure 11 — Unified Talos ramjet engine performance is shown for the Mach number and altitude relation displayed at the left of the figure. Two independent relations are presented in the main figure: (a) maximum acceleration due to thrust, and (b) deceleration due to lateral maneuver. For a given altitude, the difference between relation (a) and relation (b) gives net available acceleration along the flight path. Operating points that occur to the right of the maximum engine thrust line will result in missile slowdown.

engine thrust and deceleration resulting from lateral maneuver gives the net available acceleration along the flight path. Operating points that occur to the right of the maximum engine thrust line will result in missile slowdown.

The characteristics shown in Fig. 11 have been demonstrated by comparison with over a hundred flight tests. The mean error in the thrust-minus-drag coefficient was less than 0.01, and the 1σ scatter about the mean was about 0.01. These errors are equivalent to errors in pressure of about 1% and represent better accuracy than can be found for individual points in ground testing.

RELIABILITY

Almost 1200 missiles using the Talos ramjet engine have been launched. During 25 years of testing, an overall system success rate of 96% was demonstrated. In the ongoing Vandal program that employs the Talos airframe and propulsion system as a supersonic target, an even better reliability of about 98% is being achieved, using propulsion systems that were built about 20 years ago.

WILLIAM H. AVERY

THE TALOS BOOSTER ROCKETS

Major problems had to be solved before solid booster rockets could be produced in the size required for Talos. Five years after booster rocket development was started, booster technology had reached a level where propellants and metal parts could be tailored confidently to meet the Bumblebee Program needs. The first Talos missile was launched in 1952.

As with other parts of the Talos program, the development of rockets to accelerate a 2000-pound ramjet missile to supersonic flight speed in a few seconds required major strides into unexplored areas of technology. In 1945, only the newest types of military rockets in production were capable of attaining supersonic speeds, with payloads generally a minor fraction of rocket weight. With the freedom then available to engineer, plan, and carry out development programs, it was possible to accomplish the ramjet booster rocket objectives in only 2½ years.

As an interim measure, existing rockets were used for launching the 6-inch-diameter Cobra ramjet, the Control Test Vehicle, and the Supersonic Test Vehicle. A group of rockets, arranged in a cluster and manifolded at the forward end to equalize thrust, was used in each application. For example, four (and later six) high velocity aircraft rockets were used to launch the Cobra, four British UP-3 rockets for the Control Test Vehicles, and four T10E1 rockets (developed by Division 8 of the National Defense Research Center) for the Supersonic Test Vehicles. On the whole, these clustered boosters proved adequate, although their low impulse-to-weight ratio and the necessity of relying on the uniformity of thrust of the individual units made extension of this design to the larger vehicles and service missiles highly undesirable.

INDIVIDUAL PROBLEMS

Three major problems required solution before solid rocket boosters could be produced in sizes required by the missiles envisaged in the Bumblebee Program. The status of rocket development in 1945 is summarized in Refs. 1 and 2. The problems were: (a) the development of techniques for producing propellant grains[3] in sizes five to ten times larger than those used in the ongoing production of rockets,[4] (b) the development of special propellant granulations and compositions to achieve maximum loading density and increased overall specific impulse,[5,6] and (c) the development of propellant compositions having a greatly reduced dependence of burning rate on rocket chamber pressure to permit the use of lighter metal parts with a corresponding increase in the propulsive efficiency of the system.[7]

In addition, it was considered essential to strengthen the existing organizations engaged in solid-fuel rocket development and to establish new facilities for the experimental production of developed units.

TECHNICAL PROGRESS

The development of solid-fuel rockets five to ten times as large as those then available was a task of major magnitude. To ensure an early solution of the problem, parallel programs were initiated at Aerojet Engineering Corporation and Allegany Ballistics Laboratory (ABL), with the objective of establishing the techniques and facilities necessary for the production of large rockets.

In the fall of 1945, the decision was made to develop for use with the ramjet test vehicle (RTV) a single booster rocket having a diameter that would permit it to be inserted and attached to the 18-inch ramjet combustion chamber. Separate tasks were assigned to Aerojet and to ABL to provide a unit capable of accelerating a missile weighing 1000 pounds to a velocity of about 1800 feet per second in approximately 2 seconds.

Jet-assisted takeoff rockets that used a castable propellant made of a mixture of potassium perchlorate and asphalt had been developed previously by Aerojet. By replacing the asphalt with a polymeric resin and the potassium perchlorate with ammonium perchlorate, a propellant with a satisfactory specific impulse and reasonable physical properties was produced. The work at ABL was to be based on smokeless powder, either in the conventional extruded granulation or, preferably, in large single grains. A process for preparing grains of double-base powder[8] by the casting technique had been developed but had not been established as reliable.

AEROJET DEVELOPMENT OF BOOSTER FOR RTV

Initial emphasis was placed on development of the Aerojet booster, which was accomplished quickly. Full-scale units suitable for boosting the RTV were produced in early 1946. These rockets used a charge of two 400-pound tubular grains that were supported in the rocket chamber by circumferential tie rods. Al-

though it was known that insufficient development had been carried out to establish reliable performance of these units, the time scale of the ramjet development necessitated launching an RTV at the earliest practicable time. Therefore, five units were ordered from Aerojet and, at the same time, a program of propellant research was instituted to improve the product and to establish reproducible controls in its fabrication.

The Aerojet booster was used successfully in firing two RTV's. The first cold round to test stability and separation was fired on May 23, 1946. The second round, which successfully demonstrated ramjet operation on an 18-inch scale for the first time, was fired on September 24, 1946, 22 months after the program was started.

A third RTV and a redesigned 18-inch burner test vehicle (BTV) of reduced weight and improved airflow were launched with Aerojet boosters in January 1947. In neither instance did the rocket perform satisfactorily. Failures of the rear propellant grain occurred before the end of burning, which, in the second round, resulted in blowup of the rocket. In view of these propellant failures, it was decided to interrupt the BTV program until either the Aerojet booster could be redesigned or the ABL booster could be proved in. The discouraging results of these tests led to a vigorous effort to analyze the source of the failure. It was concluded that the tubular grain design and mode of support, combined with the marginal strength of the propellant, were inadequate to withstand the high accelerations and vibration loads imposed on the propellant during boost.

ALLEGANY BALLISTICS LABORATORY DEVELOPMENT

Although the Aerojet booster for the BTV was considered to satisfy the immediate need of the ramjet propulsion program in the original plan, the smokeless powder booster development at ABL was pursued with the objective of producing a thoroughly reliable unit with higher performance. Three alternative designs were considered to maximize the likelihood of producing at least one fully satisfactory unit. Two used extruded smokeless powder grains, and the third used full-diameter grains of cast double-base powder. The progress made in developing the casting process made it possible to terminate the two less efficient alternatives in mid-1946.

At ABL, it became apparent that there were inherent advantages in the design of a booster rocket that used a propellant bonded to the rocket case. The uniform support at the circumference greatly reduced the maximum grain stresses and also protected the case from the high temperature of the propellant gases. Thus, a more efficient and more reliable booster could be made with this design. Accordingly, after the Aerojet booster failures, all effort was turned to the development of the cast double-base booster rocket.

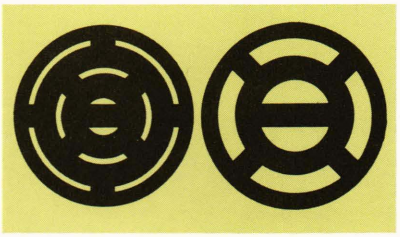

Figure 1 — Cross-section geometry of two types of powder grain used in Allegany Ballistics Laboratory (ABL) 51,000-pound thrust units. These grain geometries were designed to provide approximately constant surface area during the burning process and thus provide a constant level of thrust.

In Fig. 1, cross sections of two types of powder grain are illustrated. As a by-product of one of these, a 7-inch-diameter rocket with an aluminum case was developed that had an extraordinarily high overall specific impulse. This rocket, designated the "Deacon," was used to launch aerodynamic test vehicles for APL and for the National Advisory Committee for Aeronautics.

The development of the cast double-base booster for the BTV was completed in the spring of 1947. After five successful static tests at ABL, five launching test vehicles (LTV) with attached fins and a nose cone were flown successfully in June and July of 1947. To compensate for the absence of the BTV, a lead weight was placed in the nose cone of the LTV, which gave it a total weight that would result in about 20% higher acceleration than the BTV launch configuration to ensure a margin of safety for its use as a BTV booster.

Telemetry showed that the rocket chamber pressure during flight duplicated the static results, indicating that no propellant breakup was caused by booster acceleration and flight-induced vibrations. It was possible then to proceed confidently with adoption of the ABL booster for further ramjet testing. This confidence was fully justified by later developments. An interesting account[4] of the first 10 years of cast double-base propellant developments states that in 1956, when many thousands of boosters had been flown, not a single booster failure caused by the propellant had been recorded.

Because work leading to an improved Aerojet booster had not been completed at that time, it was decided to standardize on the ABL unit for subsequent BTV flights. The work at Aerojet was redirected along more fundamental lines. The ABL rocket performed in a highly satisfactory manner in the first BTV flight test in August 1947. A typical record of pressure and acceleration as a function of time is shown in Fig. 2. Figure 3 is a drawing of the launch configuration. This unit demonstrated a high degree of reliability and yielded telemetered pressure-time records in flight corresponding to those obtained in static firings.

On the basis of experience obtained in development of booster rockets for the BTV, work was

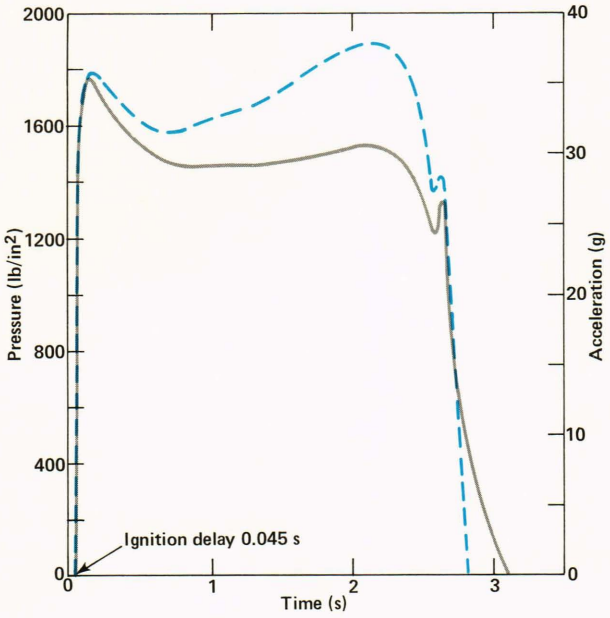

Figure 2 — Typical telemetered record of pressure (solid line) and acceleration (broken line) versus time for ABL burner test vehicle (BTV) booster shows nearly constant pressure during the rocket burn. Rocket chamber pressure is directly related to the thrust. The acceleration curve shows the effect of weight loss during the burn.

begun in January 1948 on a scaled-up version suitable for launching the XPM, the prototype Talos missile. Fabrication of the larger propellant grain, tests to tailor the thrust and burning time to the desired values, and a series of prove-in tests were completed by the end of June 1948. Increasing the size of grains produced by the casting process involved no basic difficulties and established the procedures for subsequent booster rockets for the Talos series of missiles. The first flight test of the XPM booster was made on July 1, 1948. This LTV weighed 3000 pounds and provided 90,000 pounds of thrust for 3.5 seconds. Three additional LTV's were flown between July and December while construction and tests of the XPM (dummy) airframe were in progress, and on December 2, 1948, the first flight of the booster rocket attached to the XPM airframe occurred.

That test and the following one were unsuccessful because flight instability of the launching configuration led to failure of the booster fins, although the rocket performed as predicted. This trouble was prevented on the third flight on March 30, 1949, in a flight without missile wings that demonstrated successful booster and ramjet operation. The stability problem and other program work delayed the next flight until March 6, 1950, when completely satisfactory operation was demonstrated.

With these flights, booster rocket technology had reached a state in which the propellant and metal parts could be tailored with confidence to meet new program needs, and further booster research and development turned to improvements in the specific impulse and reductions in hardware weight and cost.

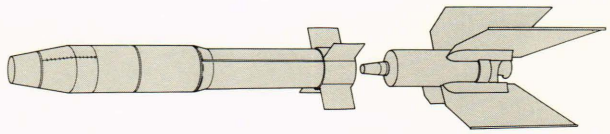

Figure 3 — BTV and launching carriage after separation. This configuration was flown successfully in 1947.

Modifications to the XPM in the spring of 1949 led to the need for a larger booster rocket, and on June 6, 1949, an LTV was launched with 105,000 pounds of thrust (average). It weighed 3720 pounds and contained 2063 pounds of propellant. Although the XPM was a prototype, the Talos missile required a still larger booster. Development of this booster, which also needed a significant reduction in the weight of the booster case and thorough prove-in of its reliability, was carried out at ABL during 1950 and 1951.

On October 28, 1952, the first Talos missile was launched. The total weight of the launching configuration was 7455 pounds. The booster alone weighed 4425 pounds. Further minor modifications were made to the booster to accommodate the requirements of the various versions of Talos over the years, but Talos booster development was essentially complete at this point. At least 1400 tactical Talos boosters were flown without a single failure during the lifetime of the Talos program.

LIQUID-FUEL BOOSTER ROCKETS

In view of possible limitations in the ultimate size of solid-fuel booster units, the development of liquid-fuel systems for short duration use was initiated at the M. W. Kellogg Company early in 1947. The objective of this work was to provide all the engineering data required to evaluate the relative merits of solid- and liquid-fuel boosters as a function of thrust and total impulse required.

Preliminary work indicated that it would be possible to design an efficient liquid-fuel rocket having thrust and duration comparable with those of the solid-fuel booster for BTV. However, the success of the solid booster development eliminated the need for liquid boosters, and further development was discontinued.

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[1] *Rockets and Underwater Ordnance*, Office of Scientific Research and Development, National Defense Research Council, Washington, D.C. (1946).

[2] R. E. Gibson, "Personal Reflections on the Origins of CPIA," *CPIA Bull.* (Oct 1981).

[3] A rocket propellant grain is a single piece of propellant of a particular geometrical configuration, developed to produce a specified rate of production of propellant gases or burning.

[4] L. G. Bonner, 12th Meeting, Joint Army, Navy, Air Force Solid Propellant Group, NOL, White Oak, Md. (7 May 1956).

[5] Specific impulse is thrust divided by weight.

[6] W. H. Avery and J. Beek, *Propellant Charge Design of Solid Fuel Rockets,* OSRD Report 5890, ABL Report 13-4, George Washington Univ. (Jun 1946).

[7] W. H. Avery, R. E. Hunt, and M. N. Donin, *Burning Rate Studies of Double Base Powder,* OSRD 8527, ABL 8-1, George Washington Univ. (Jan 1946).

[8] Highly nitrated guncotton plasticized with nitroglycerin.

LESTER L. CRONVICH

TALOS AERODYNAMICS

During development of the aerodynamic configuration for the Talos missile, several technological constraints and problems existed whose solutions added significantly to the body of design principles used in subsequent missile designs.

STATE OF THE ART IN 1945

The small group of aerodynamicists associated with the Bumblebee Program who initiated aerodynamic investigations of supersonic missiles in 1945, had limited experience in supersonic aerodynamics; their experience had been primarily with subsonic aircraft before and during World War II. The status of supersonic aerodynamics at that time was assessed at a symposium held at APL on December 6 and 7, 1945 that was attended by representatives from 49 organizations. A survey of the field revealed progress in fundamental theory, which included shock-wave theory, expansion theory, cone theory, and a method of characteristics for two-dimensional flow. For the vehicle designer there existed linear theories for bodies of revolution, for thin finite-span wings, and for ducted bodies, as well as linear and second-order theories for two-dimensional wings.

Some experimental data on projectile aerodynamics were available from the spark photography ranges of the Ballistics Research Laboratory at Aberdeen Proving Ground, Md. There were also some limited test data on small models in the two operating supersonic wind tunnels in the United States, one at the Guggenheim Aeronautical Laboratory in Pasadena, Calif., and one at the National Advisory Committee for Aeronautics, Langley Field, Va. In 1945, these were the only wind tunnels in the United States in which models could be tested at supersonic speeds, but they were too small to be of significant value for designing large guided missiles. A somewhat larger facility was available at the Ballistics Research Laboratory, but it was not yet operational. Thus, a decision was made to develop a wind-tunnel facility of sufficient size to permit testing models of approximately 1/10 scale, a size that would permit testing of relatively complicated models at desirably large Reynolds numbers. This decision led to the development of the Ordnance Aerophysics Laboratory at Daingerfield, Tex., for both aerodynamic and engine testing (Fig. 1). The aerodynamic wind tunnel eventually covered a test range of Mach numbers from 1.25 to 2.75 in a 19 × 27.5 inch test section. It proved to be the principal aerodynamics ground-test facility for the Talos program and for many other missile programs until it was closed in 1958.

Only limited flight test data were available to aerodynamicists because most supersonic testing was related to the ballistics of shells rather than to the aerodynamics of missiles. Early in the Talos program, high-velocity aircraft rockets were used as missile models for acquiring information on base pressure, drag, wing pressures, and missile accelerations attainable through deflections of movable wings. Most of the aerodynamic flight testing was carried out at the Naval Ordnance Test Station, China Lake, Calif., and later at White Sands Missile Range, N.M.

A team of associate contractors from industry and the universities was formed to assist APL in carrying out research and development in several aerodynamics areas related to the design of guided missiles. Their activities were guided by a panel of experts (known as the Bumblebee Aerodynamics Panel) whose charter was to provide broad planning of the aerodynamics program and whose goals were (a) to develop prototype information for defining an early design, (b) to develop information to improve the prototype's range and maneuverability, and (c) to foster basic research.

CONSTRAINTS IMPOSED BY OTHER TECHNOLOGIES

Low Angle of Attack for Engine

Since a key element in the development of the long-range missile was the ramjet engine, it was essential to operate the engine as efficiently as possible. This led to the decision to fly the missile at a low angle of attack, which would permit optimum engine performance, and to depend on movable wings to provide the desired maneuverability. Thus, the missile would be maintained at a small angle to the oncoming airflow while the wings would be deflected by an amount sufficient to provide the necessary lift to achieve the desired maneuverability.

Skid-to-Turn Steering

The original choice of beamriding guidance with commanded maneuvers in two orthogonal planes dictated a cruciform arrangement of wings and tail stabilizers. In addition, the wings served as control surfaces to steer the missile in pitch or yaw through de-

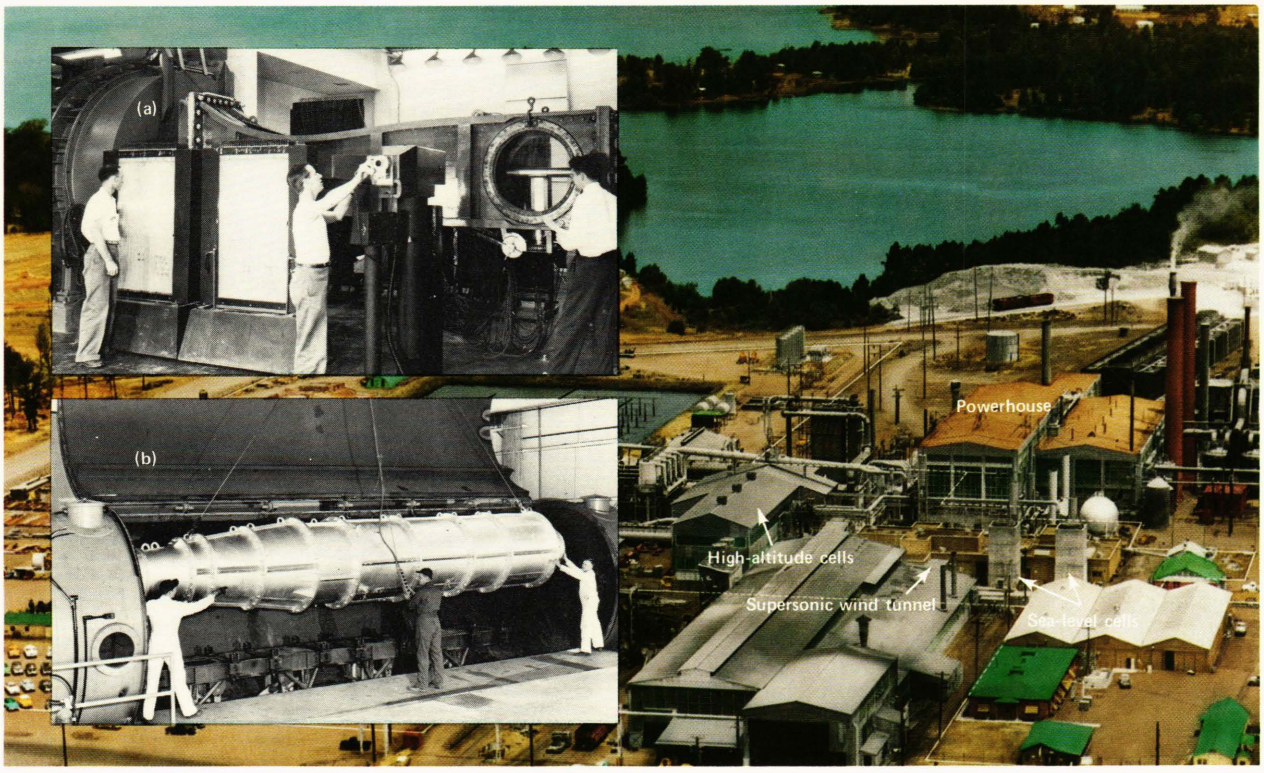


Figure 1 — The Ordnance Aerophysics Laboratory used blast-furnace blowers available at the adjacent steel plant to supply large volumes of high-pressure air for operation of a wind tunnel and burner facility. (a) Test section of the wind tunnel, where airflow from Mach 1.25 to 2.75 was available at a test section of 19 × 27.5 inches. (b) Test cell for full-scale combustor tests, where maximum air capacity was 15,000 pounds of air per minute at a pressure of 45 pounds per square inch absolute or 7500 pounds of air per minute at a pressure of 124 pounds per square inch absolute.

flections of pairs of wing panels and to stabilize it in roll through differential deflection of all four panels.

Minimum Space for Control Servos

Because the ramjet engine required a central air duct, the servos needed for operating the wing control system had to be housed in the annular region of the body around the central duct where space was limited. This restriction led to a study of wing planform shapes to find one that would result in the smallest hinge moments required to deflect the wings over the full range of operating Mach numbers and angles of attack. The planform finally selected became known as the Bumblebee planform.

Boost Phase Control

Another important factor in ramjet engine design is the need for a secondary propulsion system to boost the missile to the ramjet "take-over" speed. Thus, two aerodynamic configurations must be considered, one consisting of the missile alone and the other consisting of the missile combined with the attached rocket booster, which must fly stably until it attains the speed at which the booster can be dropped and the ramjet engine ignited for its climb to cruise altitude. The missile's relatively large wings, necessary to provide the desired maneuverability, posed a problem as a destabilizing aerodynamic surface well ahead of the center of gravity of the missile-booster combination during the boost phase. This situation required large stabilizing fins to be placed on the booster or, since space in a shipboard system is at a premium, some type of control that could permit a reduction in the size of the booster fins.

SIGNIFICANT PROBLEMS AND PHENOMENA, AND THEIR SOLUTIONS

Wing Design

A design decision was made to achieve lift primarily from the deflected wings (Fig. 2). Consideration had to be given to the problem of maximizing lift while minimizing drag, to structural requirements, and to the need for minimizing servo requirements for deflecting the wings. A combination of aerodynamic and structural considerations led to the choice of a double circular arc (biconvex) wing cross section because of its low drag per unit stress. During the subsequent production engineering phase, a modified double-wedge section was chosen, with minimum loss in aerodynamic or structural efficiency. Taper in both thickness and chord was used primarily for reasons of structural design and weight reduction. A tip rake appropriate for the Mach number regime was chosen to minimize the losses in lift associated with the tip, thus providing a more nearly two-dimensional wing lift, except for the root portion. Force testing on this so-called Bumblebee

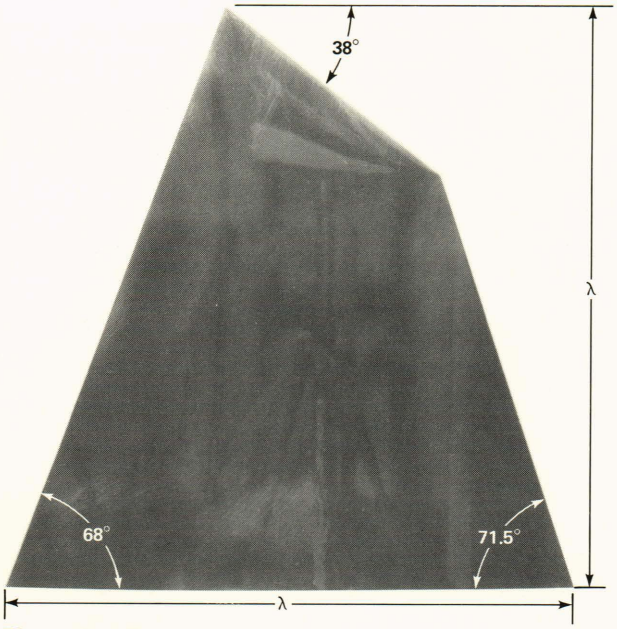


Figure 2 — The unique planform shape of the wings became known as the Bumblebee planform (from the name of the program itself). Its special shape minimized torque requirements on the servos that drove the wing controls.

planform showed rather small variations in chordwise center of pressure over the operating ranges of Mach numbers, angles of attack, and wing incidence so that it was possible to select a hinge line that minimized the design hinge moments. This particular planform shape exhibited very favorable characteristics over an extended Mach number range and has been used in nearly all other Navy surface-to-air missiles and in several non-U.S. missiles.

Roll Reversal (Tail Redesign)

Because the missile was to be roll-stabilized, it was necessary to have a roll-control system in addition to the control systems for pitch and yaw. At first, differential deflection of wings was considered for producing a roll torque and was tried in supersonic test vehicles. In flight, however, the roll obtained on the vehicle was opposite that expected from the torque produced by the wings. Because flow interaction was suspected, a research program to find the cause of the problem was established. Meanwhile, an immediate solution was to provide roll control by small flippers at the tips of the tail-stabilizing fins. Later, when the phenomena associated with this reverse roll were better understood and their effects were quantified, the tail planform was redesigned and the wings were again used to control all angular motion.

Since three angular motions (pitch, yaw, and roll) were to be controlled by four deflected panels, the choice of deflections was made definite by the use of a so-called "squeeze mode" on the wings, which required that deflections would be chosen that would minimize drag. The development of three-axis control by the wings during the missile's sustain phase led naturally to the introduction of the concept of wing control during boost.

Stabilization During Boost (Wing Control)

The early test vehicles were stabilized during boost with large booster fins that were necessitated by the presence of large wings ahead of the center of gravity of the missile-booster combination. However, the limitations of stowage and launcher space stimulated consideration of reducing the size of the booster fins by active control of the missile during the boost phase. The missile control system was designed to operate during boost as well as during sustained flight. Thus, it was possible to reduce the size (and weight) of the fins with only a small additional demand on the control system.

Duct Resonance (Exhaust Vents)

A problem that had to be faced during the flight testing program was the occurrence of resonance of the air column in the diffuser duct and combustion chamber during the boost phase when the air column was blocked by the tandem booster. Flight tests revealed a severe pressure oscillation in the duct ("organ pipe effect") that produced two problems: the pressure oscillation caused the inlet innerbody, which housed the warhead, to oscillate violently; it also prevented a clean separation of the booster from the missile, allowing the booster to recontact and damage the missile during a low point in the pressure oscillation.

The problems were solved by providing exhaust vents near the aft end of the missile to relieve the pressure buildup in the duct during boost. Because those vents were near the center of gravity of the configuration and did not alter the booster fin's effectiveness in stability, no special problems in the aerodynamic behavior of the missile were introduced.

Aeroelastic Phenomena

Because the nose-inlet ramjet engine is truly a "flying stovepipe," (i.e., a body with a large void along the center), it was expected that the design would have to account for the deflection of the missile under load and to establish the aerodynamic characteristics of the distorted configuration. Such quasi-static corrections to aerodynamics are usually needed only when the principal air load (the wing load) is applied at a point and the mass is distributed uniformly, resulting in a banana-shaped body, depending on its rigidity. For the Talos missile, it was found that at low altitudes the flexibility of the structure caused a considerable reduction in the maneuverability achievable per unit deflection of the wings (Fig. 3). The forward portion of the missile (diffuser ducting section) was less rigid than the aft portion (combustion chamber section). However, for a given maneuver, the angle of attack and control incidence increased with altitude, and these angles caused a redistribution of air loads, which must balance the fixed inertia loads. Thus, at high altitudes (such as 60,000 feet) that redistribution of loads caused the body to behave more like a rigid body.

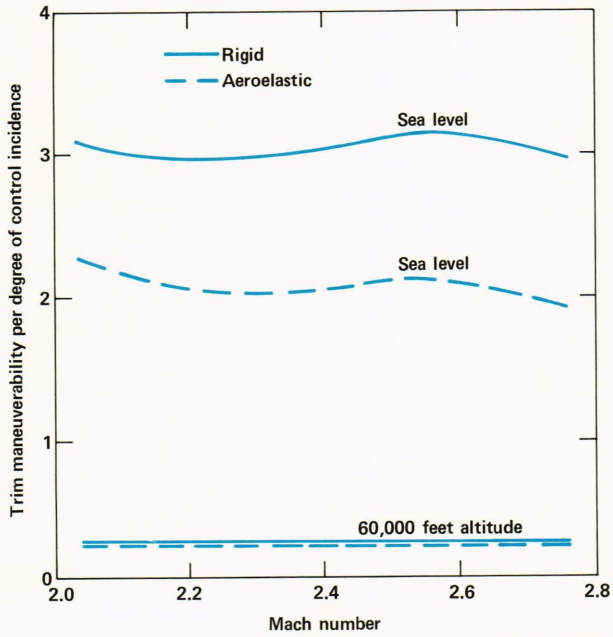


Figure 3 — The aeroelasticity of the missile under the high loading at sea level reduces the attainable maneuverability for a given wing incidence to two-thirds of that available for a rigid missile. At higher altitudes, the effect is negligible.

Effects on Later Missile Programs

As noted earlier, the modified double-wedge cross section for the wing with the tapered planform and raked tip (i.e., the Bumblebee planform) was found to have desirably low hinge-moment characteristics. The planform has been used over a wide range of Mach numbers for control surfaces of many other missiles, including the Terrier, Tartar, and Standard missiles of the United States, the French Masurca, the Italian Indigo, and the British Bloodhound. A somewhat similar planform appears on the British Sea Dart and the Russian Atoll and Gainful.

The procedure followed in the Talos program to account for the effects of elasticity of the missile on the static aerodynamics was also applied to the nose-inlet, wing-tip-controlled Long Range Typhon missile of the early 1960's. On the basis of previous Talos experience, it was decided to vent the diffuser pressure during boost of the Long Range Typhon missile through openings in the adapter section between the missile and the booster to avoid the "organ-pipe" oscillations in the duct. In addition, as further experience was gained in operating the inlets at higher angles of attack, it became evident that the restriction to low angles of attack (requiring wing incidence for lift) could be partially removed. In fact, the Long Range Typhon test vehicle used large fixed wings with wing-tip controls and achieved maneuverability through body angle of attack with satisfactory engine performance.

Thus, the Talos aerodynamic program, lacking an adequate supersonic aerodynamics data base, had to embark on a course that generated a new body of aerodynamic data and design principles. These were in the fields of aerodynamic stability, forward surface control, wing-body and wing-tail interference, aeroelastic effects on static aerodynamics, and inlet effects on aerodynamics. A control surface shape, the well-known Bumblebee planform, was developed that minimized center-of-pressure travel.

JOSEPH GULICK, W. COLEMAN HYATT, and OSCAR M. MARTIN, JR.

THE TALOS GUIDANCE SYSTEM

The Talos guidance system evolved from a series of development efforts within the Bumblebee and Talos programs — specifically, the first beamriding system and the first semiactive interferometer homing system. The guidance system that evolved was virtually unjammable, and it provided the missile with capabilities against manned aircraft, antiship missiles, surface ships and boats, and radar targets.

INTRODUCTION

When the Bumblebee Program was conceived, missile guidance technology was in its infancy. The early guidance development work was based on pulse radar technology since pulse radars were well developed by 1945. The first guidance concept was that a radar beam, following the target, could be used to guide the missile to the target. It was determined early, however, that the maximum allowable miss distance could not be achieved by such a "beamriding" system at ranges beyond approximately 10 nautical miles. When the target intercept range for the missile was increased, the guidance concept was revised to use beamriding for the midcourse phase with semiactive homing for the terminal phase. This resulted in a guidance system that produced very small miss distances, essentially independent of intercept range. During the later Talos years, the major guidance effort was focused on the homing system. This effort resulted in a monopulse homing system that was virtually unjammable and an antiradiation missile seeker that enabled the missile to home on radar targets.

MIDCOURSE GUIDANCE

In a beamriding system, departure of the missile from the axis of a conically scanned radar beam causes deflection of the aerodynamic surfaces to return the missile to the beam axis. Basically, the missile must determine the vector that indicates the angular direction and distance to the scan axis. The distance is determined by observing the amplitude of the modulation produced by the conically scanned beam, and the angular direction is determined by the phase of the amplitude modulation with respect to the scan frequency reference signal.

The beamriding system for Talos was the result of a joint effort by APL and Farnsworth Television and Radio Corp. It employed a conically scanned radar beam (Fig. 1) and, together with a sinusoidal variation of the pulse repetition frequency, provided the missile-borne receiver with the signals needed to measure missile angular distance and direction perpendicular to the nutation axis of the guidance beam (Fig. 2). The missile was roll stabilized in flight by a free gyro so that the error signals would be directed to the proper aerodynamic steering surface.

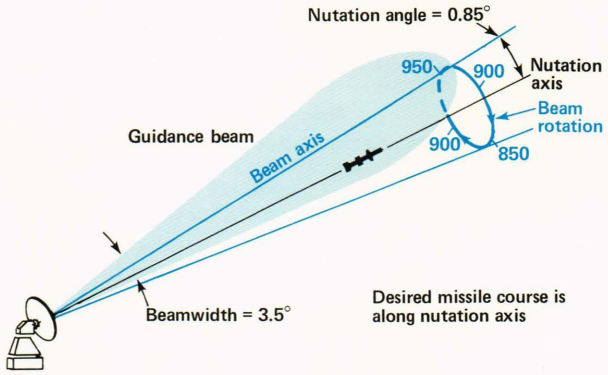


Figure 1 — The guidance beam for the beamrider missile was conically scanned at 30 hertz with a clockwise rotation, as viewed from behind the radar antenna. The radar pulse rate, nominally 900 pulses per second, was varied by ±50 pulses per second in synchronism with the conical scan.

The guidance transmitter radiated pulse groups at a nominal rate of 900 pulses per second. Each group consisted of three pulses that were coded by interpulse timing to identify the guidance beam to the missile. Nutation position information was transmitted by frequency modulating the pulse group rate at the nutation frequency (30 hertz) with a deviation of ±50 groups per second. The maximum pulse group rate occurred for a nutation position that was up and left. On board a ship, an inertial system was required to compensate the pulse group modulation for roll and pitch.

A simplified block diagram of the beamrider receiver is shown in Fig. 3. Microwave pulses were detected and passed through a decoder to produce one pulse for each valid code group. The decoded pulses were then applied to a 30-hertz amplitude detector, a 30-hertz frequency modulation detector, and a beacon transmitter. Outputs from the frequency modulation detector were used as references for the

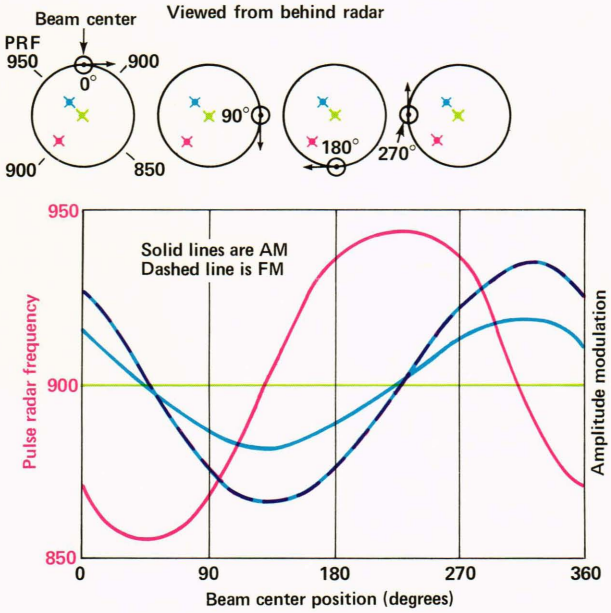


Figure 2 — Signal modulations detected by the beamriding receiver were processed to determine missile position with respect to the guidance beam. Angular direction and distance from the scan axis were determined by comparing the phase and amplitude of the 30-hertz amplitude-modulated signal with the frequency-modulated reference signals.

steering channel phase comparators. The phase comparators were used to resolve the in-phase component of the amplitude modulation detector output to obtain steering-error signals for each wing plane.

As a flight progressed, the direction of the guidance beam was programmed by the fire-control computer to cause the missile to fly the desired midcourse trajectory. Missile range was determined by automatically range tracking the missile-borne beacon pulses. That range was used by the fire-control computers to control the beam program and compute the time at which a homing enable pulse code was transmitted to the missile, permitting target acquisition by the homing system.

Subsonic beamriding along a fixed beam was accomplished by a guidance test vehicle in January 1947. The first supersonic beamriding Talos was demonstrated in 1950.

TERMINAL GUIDANCE

A terminal-guidance phase following the midcourse beamriding phase had been envisioned from almost the beginning of the development program. The task was to devise a homing system that would be compatible with the constraints imposed by the ramjet diffuser and that would rapidly acquire the target without requiring accurate missile-to-target line-of-sight positioning information. The goal of intercepting small targets at long range (about 100 nautical miles) placed a premium on high receiver sensitivity as well as on good target resolution.

The interferometer homing system was chosen for terminal guidance for the following reasons:

1. Widely spaced body-fixed antennas were compatible with ramjet inlet constraints.
2. The body-fixed antennas were simple compared with a gimballed dish antenna.
3. Rapid target acquisition was possible without the need for missile-to-target angle data.
4. It was desired to have the largest possible aperture and, hence, the most accurate measurement of the line-of-sight angular rate.

The basic principle of the interferometer system is illustrated in Fig. 4. Two widely spaced antenna elements of an interferometer have a composite antenna pattern consisting of a series of peaks and nulls. The peaks and nulls are moved by a phase shifter, resulting in amplitude modulation of the target signal. A discriminator tuned to this modulation frequency provides an output that is proportional to the angular rate of the target line of sight. If the target line-of-sight rate with respect to an inertial reference is maintained at zero, a proportional navigation homing trajectory to the target is executed. It is therefore only necessary to control the missile turning rate so that the line-of-sight rate is maintained at zero to effect an intercept.

THE FIRST TALOS HOMING SYSTEM

Guidance concepts consisting of body-fixed, widely spaced antennas to be used as a radar interferometer were proposed almost simultaneously by the Defense Research Laboratory (DRL) of the University of Texas and the Massachusetts Institute of Technology. Both concepts used widely spaced antennas but different methods of signal processing. Because the basic system proposed by DRL (which employed an independent interferometer channel for each wing-control plane) was judged to be more consistent with the state of the art, the first Talos homing system was based on that concept.

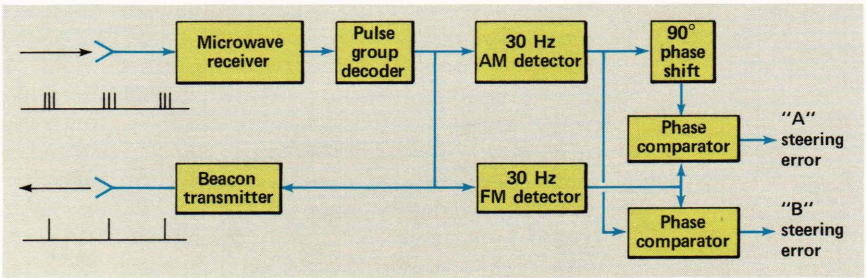


Figure 3 — The beamrider receiver detected and processed guidance beam signals to generate commands for the missile control planes and the radar beacon responses.

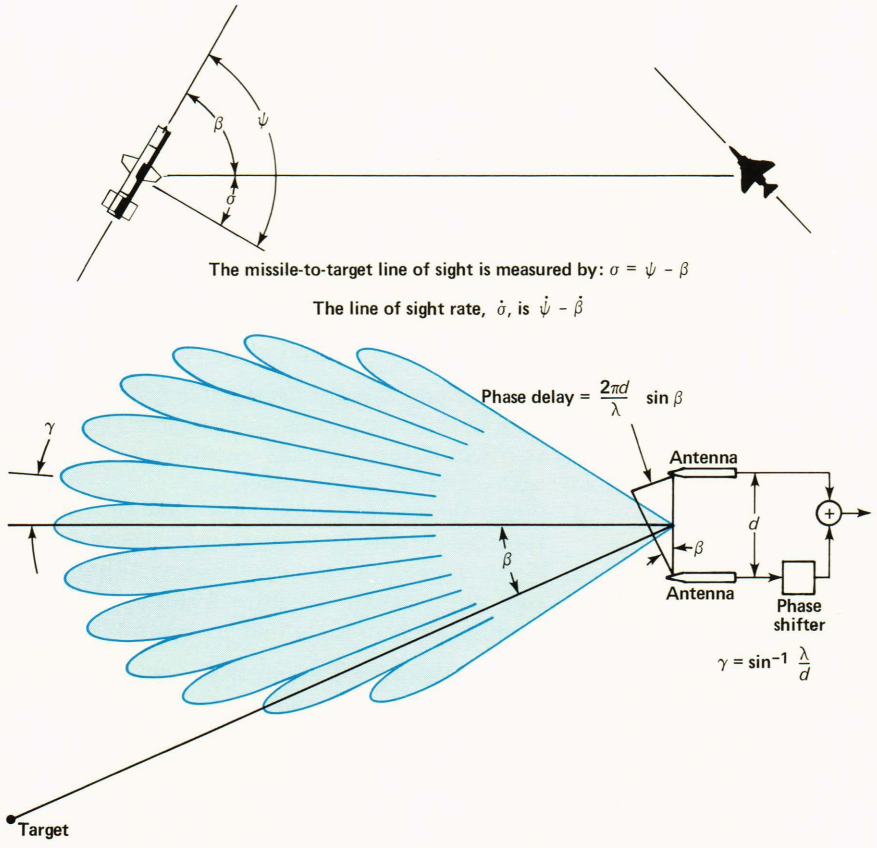

The missile-to-target line of sight is measured by: $\sigma = \psi - \beta$
The line of sight rate, $\dot{\sigma}$, is $\dot{\psi} - \dot{\beta}$
Phase delay = $\frac{2\pi d}{\lambda}$ sin β
Antenna
Antenna
Phase shifter
$\gamma = \sin^{-1} \frac{\lambda}{d}$
Target

Figure 4 — Interferometer parameters and symbols used in the article are defined in this figure.

The receiver (Fig. 5) used a scanning interferometer system. Target signals at the antenna were:

$$\begin{aligned} X_1 &= A_1 \sin \omega t \\ X_2 &= A_2 \sin (\omega t + \theta) \\ &= A_2 \sin \left(\omega t + 2\frac{\pi d}{\lambda} \sin \beta\right), \end{aligned} \tag{1}$$

where ω is the microwave frequency and θ is the electrical phase difference at the antennas. A_1 and A_2 are the amplitudes, which may be different, but the scanning process was essentially insensitive to that difference. The scanning phase shifter advanced the phase of X_2 by $\Phi(t)$ as follows:

$$\Phi(t) = \omega_S t + \Phi, \tag{2}$$

where ω_S is the scan frequency and Φ is the initial phase shift. The X_3 can be written as

$$X_3 = A_2 \sin \left[\left(\omega + \omega_S + 2\frac{\pi d}{\lambda} \dot{\beta} \cos \beta\right) t + \Phi \right]. \tag{3}$$

The addition of X_3 and X_1 gives X_4:

$$\begin{aligned} X_4 &= A_1 \sin \omega t \\ &+ A_2 \sin \left[\left(\omega + \omega_S + 2\frac{\pi d}{\lambda} \dot{\beta} \cos \beta\right) t + \Phi \right]. \end{aligned} \tag{4}$$

X_4 can be seen to be a carrier signal at ω and is amplitude modulated at

$$\omega_S + 2\frac{\pi d}{\lambda} \dot{\beta} \cos \beta. \tag{5}$$

The heterodyne process in the receiver changed the carrier from microwave to a lower frequency but did not affect the modulation and, therefore, did not change the basic $\dot{\beta}$ information. It is also apparent that because the desired information was the frequency of the modulation, changes in amplitude of the signal had no direct effect upon the measurement of $\dot{\beta}$. Decoupling of body motion to provide the line-of-sight rate measurement ($\dot{\sigma}$) was accomplished by use of a body-mounted rate gyroscope where the gyro output frequency modulated an oscillator to produce a carrier frequency (ω_0) with a deviation proportional to the missile body turning rate ($\dot{\psi}$). The term N in the gyro channel was an estimate of cos β. A fixed value of N for all flight conditions proved to be unsatisfactory. Therefore, Talos had a selection of two values based upon the crossing component of the target speed. That value was set into the missile at the time of launch. Double modulation eliminated the scan-

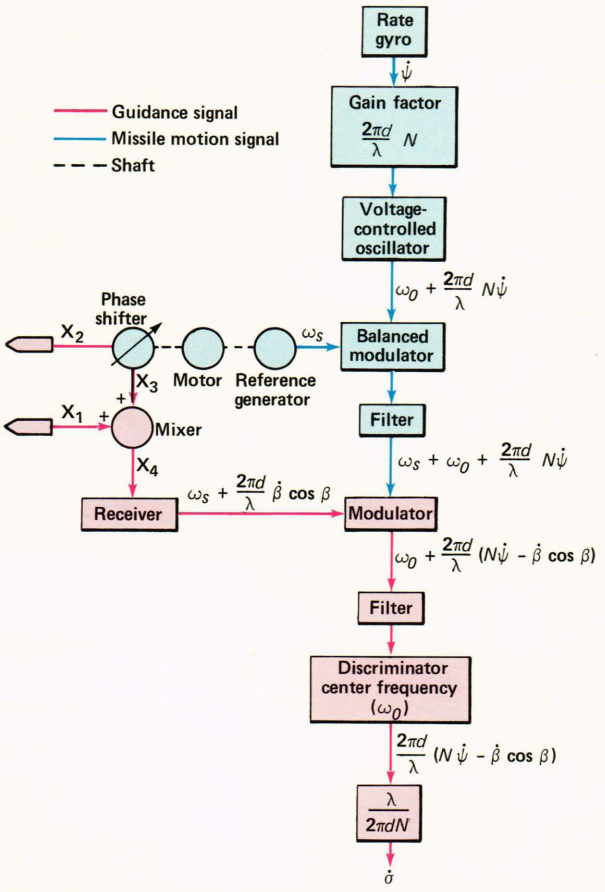


Figure 5 — The first Talos homing receiver (1950) used a scanning interferometer. The system shown here was for a single control plane. An identical system was used for the orthogonal control plane. Output from a body-mounted rate gyro was used to decouple the effect of body motion on the interferometer signals. The term N was an estimate of cos β. The output from the discriminator was a signal proportional to $\dot{\sigma}$.

phase shifter frequency (ω_S) from the final term and allowed a frequency discriminator tuned to ω_0 to provide an output that was proportional to $(2\pi d/\lambda)$ $(N\dot{\psi} - \dot{\beta} \cos \beta)$. The discriminator output, neglecting biases, was approximately proportional to the desired $\dot{\sigma}$. This form of signal processing was used in a number of test flights and for the first Talos production receiver.

STABLE PLATFORM PHASE FOLLOW-UP SYSTEM

Two major problems associated with the first Talos homing system were the following:

1. A bias resulted from any offset between the voltage-controlled oscillator and the discriminator center frequency,
2. A stable gyro gain factor equal to $(2\pi d/\lambda)N$ was difficult to maintain.

Both problems were solved by the Stable Platform Phase Follow-Up System (STAPFUS).

The scanning interferometer using STAPFUS is shown in Fig. 6. As before, a motor drove the phase shifter and a reference generator. A single-degree-of-freedom free gyro was coupled to a synchro-resolver to make phase corrections for missile body motion. The gear ratio between the gyro and resolver provided a constant gain factor for the gyro coupling. The difference in phase between the reference signal and the interferometer signal was obtained by the rotor shaft position in a phase-following servo. A potentiometer driven by the phase servo provided an output that, when differentiated, was a measure of the desired line-of-sight rate. Differentiation after the phase-subtraction process eliminated bias. A simple initializing circuit was provided to ensure that the potentiometer started at the zero position. There was no inherent bias in the system because the source of the bias had been eliminated.

Shortly after the incorporation of STAPFUS into the missile system, it was realized that a phase detection of the two signals driving the phase servo could provide an excellent indication of the presence of a signal suitable for steering, especially in a home-on-jammer mode. For this reason, a phase detector was eventually included in a major receiver design program to support home-on-jammer operations.

STAPFUS proved to be an extremely precise measurement system; after it was incorporated into the Talos missile, the majority of the intercepts resulted in direct hits (Fig. 7).

DEVELOPMENT OF THE CONTINUOUS WAVE INTERFEROMETER HOMING SYSTEM

During the 1950's, the microwave pulse-interferometer homing system was developed, and capability against medium-to-high-altitude targets was successfully demonstrated. During that period, the application of Talos to low-altitude targets, particularly over land, was being explored. In that situation, the target-tracking radar, operating at low elevation angles, illuminated the earth's surface and resulted in a large clutter signal that obscured the target (Fig. 8).

The technique developed in the Talos Program to permit low-altitude operation made use of the familiar Doppler effect. Because of the incoming target's velocity, its reflected radar signal is slightly higher in frequency than is the return from the clutter, which is stationary. This frequency separation is the unique signal characteristic that permits rejection of the undesired clutter signals. Tracking the target Doppler signal with a narrow bandpass filter effectively eliminates the massive clutter signals. A typical spectrum of the Doppler signals received by the missile in flight is shown in Fig. 9.

Attention was first given to the excellent work by Raytheon on the Lark (DPN-15) and the Sparrow (DPN-24) homing systems. The initial work on the continuous wave (CW) interferometer for Talos used much of the circuit design of those systems. Six flight

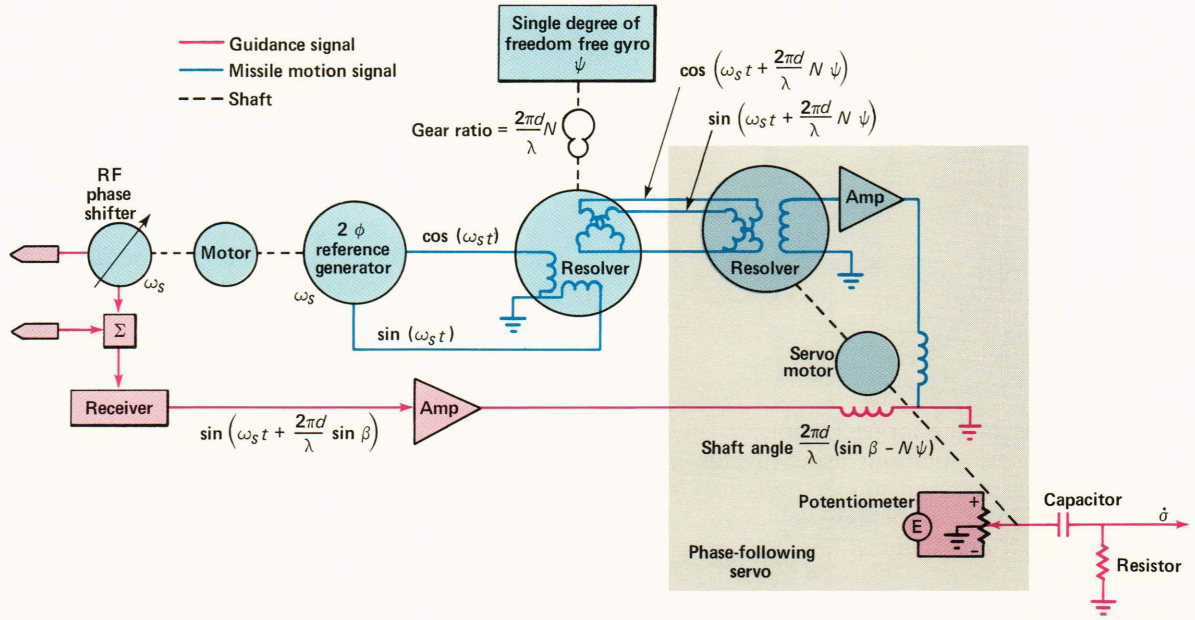


Figure 6 — STAPFUS was a more precise method for decoupling body motion from the scanning-interferometer output. The figure shows a single control channel. A synchro-resolver mechanically coupled to a free gyro (stable platform) was used to shift the phase of the reference generator. A phase-following servo positioned the resolver shaft at an angle that corresponded to $(2\pi d/\lambda)$ (sin β – $N\psi$). That shaft was also coupled to the arm of a potentiometer. The output from the potentiometer was differentiated by a resistor-capacitor network and resulted in a signal proportional to $\dot{\sigma}$.

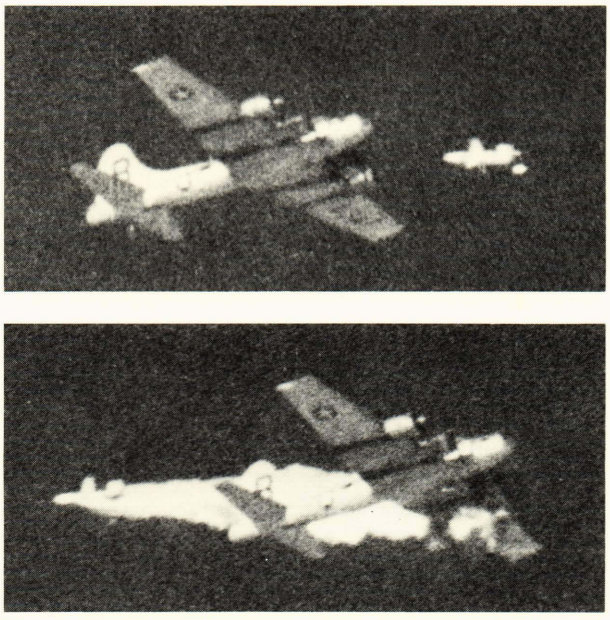


Figure 7 — Miss distances were reduced significantly following the introduction of STAPFUS. The B-17 target shown in this figure was destroyed by a direct hit. The warhead was not used in this test.

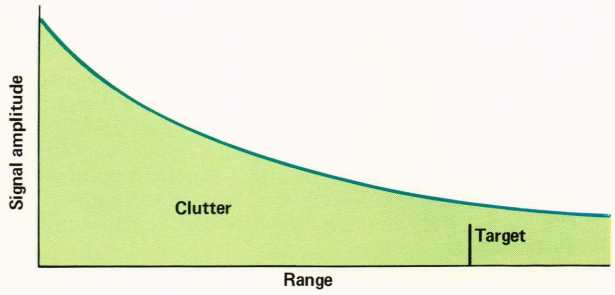


Figure 8 — Pulse radar signals from a moving target can be obscured by large, stationary reflecting surfaces such as the sea or land masses.

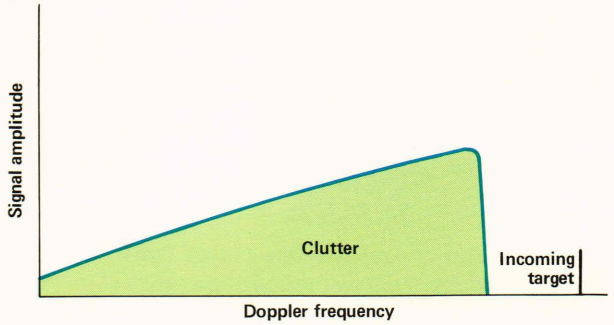


Figure 9 — Continuous wave (CW) radar signals from a moving target can be detected by filtering at the Doppler frequency.

tests were made during 1955-56 using the Sparrow homing-system design but modified for an interferometer antenna system. These tests revealed or confirmed the existence of characteristics that would need to be significantly improved to meet the goals set for the Talos homing system.

The Talos CW homing receiver was designed around the following features:

1. The superheterodyne receiver used quartz-crystal filters to establish a stable and narrow

bandpass that would remove the clutter signals from the target signal.

2. The klystron local oscillator, used in the conversion of the microwave input signals to an intermediate frequency, was controlled by phase-locking the klystron to the illuminator signal from the fire-control radar. That was essential if the target signal was to be kept within the narrow passband (100-hertz bandwidth) of the receiver. The phase-lock loop also provided a convenient way to offset the klystron frequency for automatic tracking of the target Doppler signal.
3. A prediction of the target Doppler frequency, based upon computations using measurements from the target- and missile-tracking radars, was transmitted to the missile to aid in the target search and acquisition function of the receiver. This feature reduced the initial Doppler search bandwidth from 50 kilohertz to 3.5 kilohertz and provided target acquisition in less than 2 seconds in most cases.
4. The solid-state circuit design provided low package volume, stability of adjustment, and immunity to vibration and shock.
5. The missile-to-target angle-measuring system of the interferometer was retained because of its precision and other advantages for the Talos ramjet configuration.

With the timely availability of cavity-stabilized, high-power (1 to 5 kilowatts) klystron amplifiers for the CW radar illuminator, the missile could operate against small aircraft at a range of 100 nautical miles, which coincided with the improved range of the ramjet at that time.

Figure 10 is a block diagram of the phase-locked klystron loop and the ground-aided acquisition loop. The klystron was electrically pretuned prior to launch to the approximate frequency of the illuminator. Automatic frequency control pull-in occurred at the time the ship-based CW illuminator began radiating, about 15 seconds before intercept. The target Doppler frequency, f_D, was computed using radar data and transmitted to the missile by a 400-kilohertz plus f_D frequency modulation on the illuminator frequency. That estimate of the Doppler was used in the ground-aided acquisition loop to establish the initial frequency for the voltage-controlled oscillator. In that way, the klystron frequency was very close to the correct value, and only a minimal search was required to acquire the target.

Figure 11 includes the front receiver with its narrowband quartz crystal filters and discriminators, and the Doppler tracking loop. The loop served to control the voltage-controlled oscillator and, therefore, the klystron in order to keep the target signal in the center of the receiver's narrow bandpass. As long as tracking of the target Doppler signal was maintained, the interferometer angle data could be processed by the STAPFUS system to steer the missile.

The SAM-N-6c1 Missile with its CW homing receiver had some fundamental characteristics that contributed to the missile's capabilities in a countermeasures environment. First, there was limited exposure to the hostile environment as a result of the narrowband characteristics of the seeker and the short (6 to 10 second) homing time. Second, the high-speed phase-tracking loop in STAPFUS provided a nominal angle-tracking sensitivity (volts per degree per second) when it was tracking, independent of the signal-to-noise ratio. Finally, inherent in the Talos phase-interferometer angle processing was the capability to resolve signals from two or more separate sources (for example, from multiple noise jammers) if there was a small power difference ($\geq$2 dB) between them.

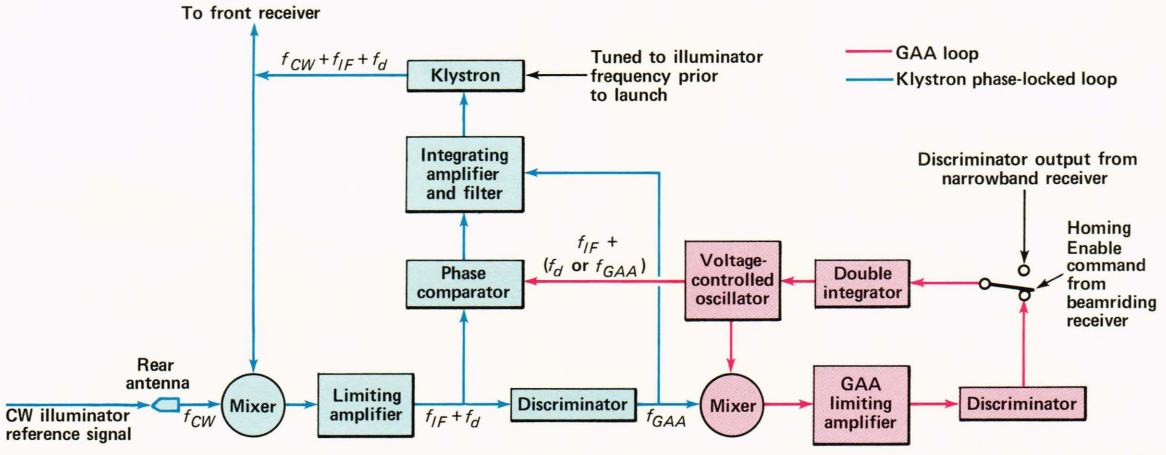


Figure 10 — The rear reference receiver used a phase-locked klystron and a ground-aided acquisition (GAA) loop. The klystron frequency was coarsely corrected by the discriminator to the frequency of the illuminator signal, followed by exact frequency control by the phase-locked loop. The voltage-controlled oscillator frequency was offset from the intermediate frequency by the f_{GAA} loop and caused the klystron frequency to be offset precisely for the target signal entering the front receiver (see Fig. 11).

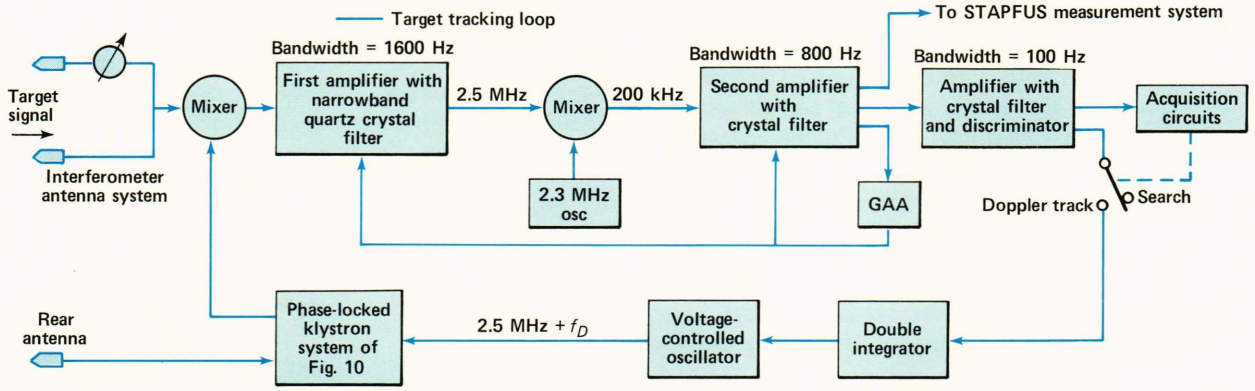


Figure 11 — A target signal having a Doppler frequency equal to f_{GAA} would pass through the amplifiers and narrow-bandpass quartz crystal filters and be detected by the acquisition circuit. Upon detection, the discriminator output readjusted the frequency of the voltage-controlled oscillator to keep the target signal in the center of the receiver bandpass. The narrow-bandpass filters removed the land and sea clutter signals entering the antennas.

As the flight test program proceeded, it became of interest to determine if the CW guidance system would perform well against surface targets. In this application, the target signal and the sea clutter signals do not have a useful Doppler frequency separation. But the combination of the 800-hertz and 100-hertz filter bandwidths maintained a signal-to-clutter ratio suitable for guidance. Figure 12 shows the massive destruction of a destroyer escort vessel as the result of a direct hit by a Talos missile.

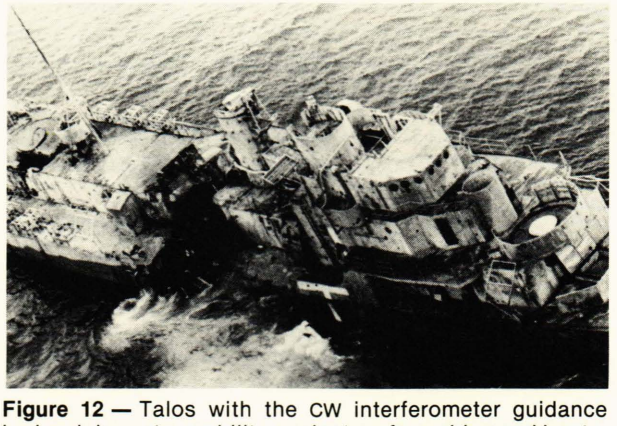


Figure 12 — Talos with the CW interferometer guidance had an inherent capability against surface ships and boats. The capability to engage these targets at ranges well beyond the radar horizon and in the presence of extensive land clutter required only minor changes to the missile and to the shipboard fire control system. The missile for this intercept did not have an active warhead.

MONOPULSE* HOMING SYSTEM

The original SAM-N-6c1 Missile performed extremely well against many types of jamming — its capabilities far exceeded those of any other missile of its day. However, its RF sequential lobing (scanning) angle processing, its slow automatic gain control, and its time-consuming Doppler search routines limited its capabilities against some types of deception countermeasures.

One of the principal objectives of the monopulse seeker design was to enable the missile to win any one-on-one encounter with an aircraft employing any conceivable AM and/or FM noise or deception jamming, even if the designer of the jammer had full knowledge of the Talos guidance system. By the mid-1960's, a seeker emerged that was virtually unjammable by an attacking aircraft. However, the system was not introduced to the Fleet until 1971 because of the high-priority antiradiation missile effort.

Two different monopulse receiver concepts were initially examined. APL examined the concept that took the intermediate frequency (IF) signals associated with antenna pairs and, after the narrowband filtering, multiplexed them into a common IF. Meanwhile, Bendix pursued the idea of the parallel channel, that is, two IF's in parallel for each guidance plane. With the solid-state technology that existed in the early 1960's, the parallel-channel concept became the most attractive: it lent itself to the use of hard-limiting IF's (no automatic gain control; phase tracking appeared satisfactory; the four IF's could be packaged within the same volume occupied by the two IF's in the original CW homer; and it would provide a simpler design than would be possible with a multiplex receiver.

One requirement for the Talos monopulse seeker was that it be compatible with the existing STAPFUS. STAPFUS, as discussed earlier, required a scan reference (ω_S) and a scan ($\omega_S + (2\pi d/\lambda) \sin \beta$) signal. As illustrated in Fig. 13, the Talos monopulse receiver was designed to provide those two signals. The receiver can be likened to the scanning receiver, with the exception that a pseudo scan was introduced at IF following narrowband filtering. That was accomplished by offsetting the frequencies of the second IF amplifiers by an amount equal to the pseudo scan. To ensure that the pseudo scan would not be vulnerable to electronic countermeasures (ECM), the scan

*The word "monopulse" is often used to describe a missile guidance system that employs simultaneous lobe comparison and may or may not employ pulses. For Talos monopulse, the signals were CW.

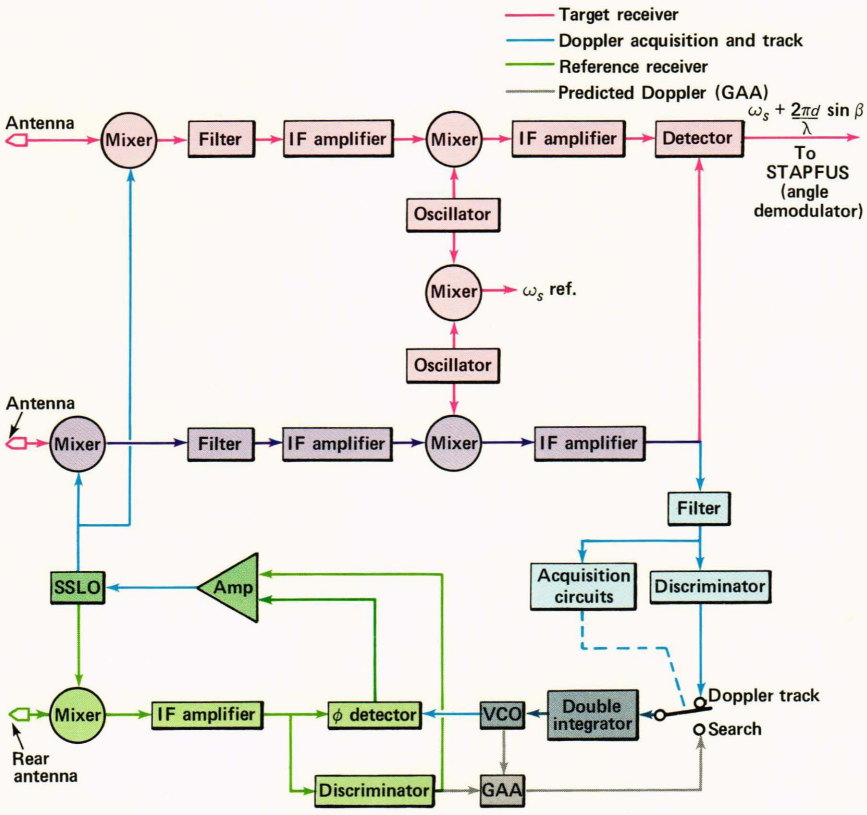


Figure 13 — The monopulse seeker was a refinement of the original CW seeker. The target and/or jammer signals were processed through a two-channel receiver (per guidance plane). Narrowbanding occurred almost immediately following the microwave mixers. The intermediate frequency (IF) amplifiers were hard limited on receiver noise. The Doppler tracking loop was closed through the microwave local oscillator and the first mixer. Predicted Doppler information provided by the ship was used to aid target search. The home-on-jamming mode employed the same narrow bandwidth and angle processing circuits used for tracking the target echo.

reference was chosen to be greater than the bandwidth of the narrow input filters. There was also a conversion of the scan signals and the scan reference signals to the lower frequency signals required by STAPFUS.

The Doppler search routines in the original CW seeker were deficient in that target reacquisition was slow or in some cases could be prevented entirely. Two contributing characteristics were the relatively slow sweep-repetition rate and the total reliance on memory for positioning the sweep. The original search patterns had been designed to provide a high first-look acquisition probability under minimum-signal-level conditions. That limited the maximum search speed that, in turn, was in conflict with the electronic counter-countermeasures requirement for fast reacquisition. Reacquisition must be fast since a jammer can cause the seeker to lose acquisition repeatedly throughout the homing phase. A compromise was sought for the monopulse seeker wherein the sweep speed was increased to a point where the single-look probability for the small signal case was lower than before but, after a second or two, was comparable because of the increased number of looks. Late in the homing phase, when the target signal-to-noise ratio was relatively high, the probability of single-look acquisition was essentially unity and, thus, the desired fast reacquisition was achieved. The problem of positioning the Doppler search center was alleviated by using the predicted Doppler information provided by the ship during the homing phase. The new search routines ensured continuous STAPFUS angle tracking under virtually all conceivable electronic countermeasures conditions and made the system far more tolerant of Doppler prediction errors.

The control of critical guidance functions was based on the coherency of the angle data. That provided a way to resolve a signal emanating from essentially a point source forward of the missile (target skin echo or a jammer) from other signals such as sea clutter, scattered chaff, receiver noise, and so on. There was no need for a detector dedicated to the home-on-jammer (HOJ) mode. The only circuit dedicated to HOJ was the HOJ timer, which delayed guidance switchover from midcourse to homing in cases where acquisition of the target echo was not achieved immediately. That was to prevent immediate HOJ on a standoff jammer. The guidance control logic is shown in Fig. 14.

TESTS OF THE CW AND MONOPULSE HOMING SYSTEM

Extensive laboratory testing of the CW and monopulse homing systems was conducted by the countermeasures group at the Naval Ordnance Laboratory, Corona, Calif. The results of that evaluation provided convincing evidence that the Talos missile with the monopulse seeker would be virtually undefeatable by any self-protection noise or deception jammer. Twenty-five of the 26 valid flight tests of the

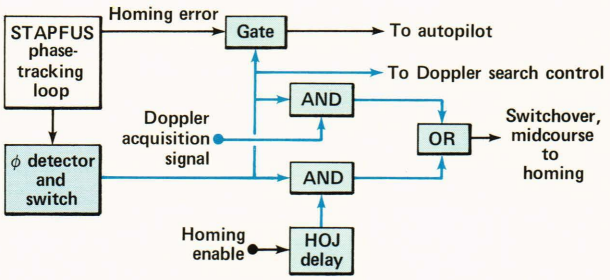


Figure 14 — Guidance-control logic used to implement guidance switchover from midcourse to homing, to gate the steering information once homing began, and to control Doppler-search routines was based on the coherency of the angle data. The signal used for that was obtained from a phase detector that monitored the STAPFUS phase-tracking loop.

Unified missile were successful. Of the 25, nine were with the monopulse seekers against a broad selection of electronic countermeasures types and parameters. Two of the successful tests were against multiple jammers, one of which is shown in Fig. 15.

An interesting observation can be made about how self-protection jamming affected the guidance accuracy (miss distance) of the Talos monopulse missile (see Fig. 16). Note that the Talos performance against the jamming targets was superior to that against the nonjamming targets. This is understandable when one recognizes that a jammer generally provides point-source enhancement of the target; that is, it literally provides a beacon that the missile can home on.

DEVELOPMENT OF MULTIMODE/ MULTIBAND HOJ SYSTEM

The long-range capabilities of Talos made it a desirable weapon to engage standoff jammers or to force them to remain at great distances. However, there was a guidance problem. If the Fleet's surveillance and fire control radars were jammed so as to deny good information about the location of the jammers and the jammers were indeed at long ranges, the midcourse guidance could not be programmed to put the missile close enough to the jamming aircraft for reliable semiactive homing.

The principal objective for the multimode multiband HOJ homing system was to enable the missile to home on jammers in S, C, and X bands. If the missile could home on one of the jammers, the midcourse guidance requirements could be relaxed. All of the semiactive and on-frequency HOJ capabilities of the monopulse homing system were to be retained. A secondary objective was to enable the missile to home on radars operating in those bands. Finally, the homing system had to be compatible with existing Talos missiles, with easy retrofitting possible. Changes to the midcourse guidance were also defined that would have extended the missile's range. Two complete guidance kits were fabricated, but the system was not introduced into the Fleet because of the planned deactivation of Talos.

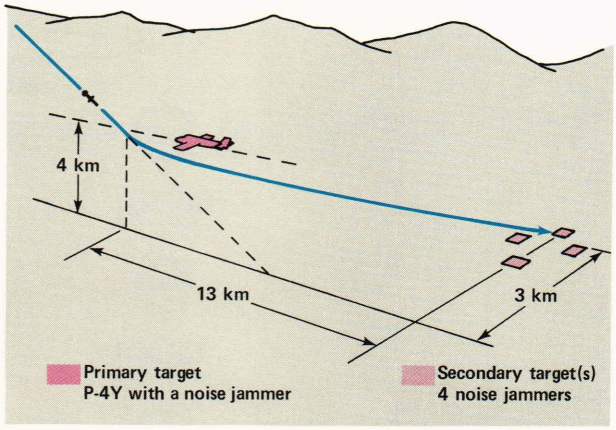


Figure 15 — Multiple jammer flight tests were conducted to demonstrate dichotomous angle-tracking capabilities inherent in the Talos interferometer guidance system. Briefly, if signals from multiple sources were present simultaneously, the missile would track one of them if a power differential of 2 decibels or greater existed within the narrow bandwidth of the receiver. In practice, the missile would nearly always intercept one of the targets. For the multiple jammer test illustrated here, the primary target was a P-4Y aircraft with a noise jammer. After achieving a near miss on the aircraft, the missile successfully intercepted the westernmost jammer on the ground.

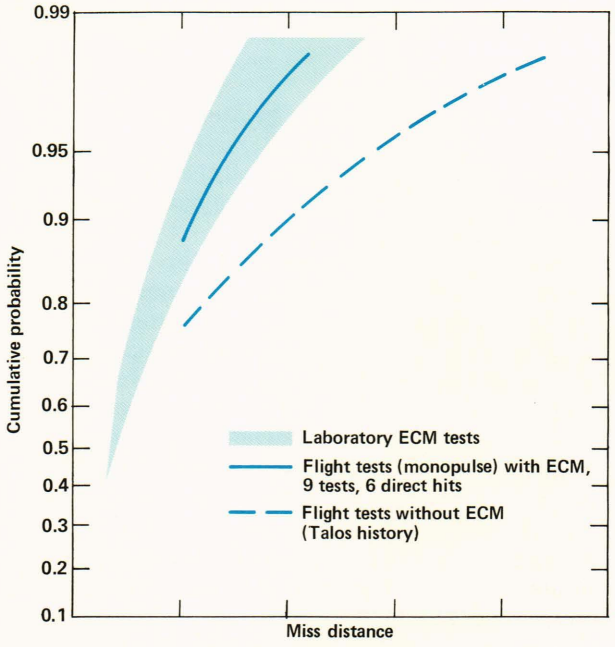


Figure 16 — The effect of self-protection electronic countermeasures (ECM) on miss distance is illustrated. The curves were derived from miss distance data obtained from laboratory ECM tests conducted at the Naval Ordnance Laboratory, Corona, Calif., from the monopulse flight tests against jamming targets, and from historic test data of Talos flight tests against nonjamming targets. Note that the performance against the jamming targets was superior to that against the nonjamming targets.

A simplified block diagram of the homing system is shown in Fig. 17. The basic system was the semiactive monopulse seeker. The principal modifications

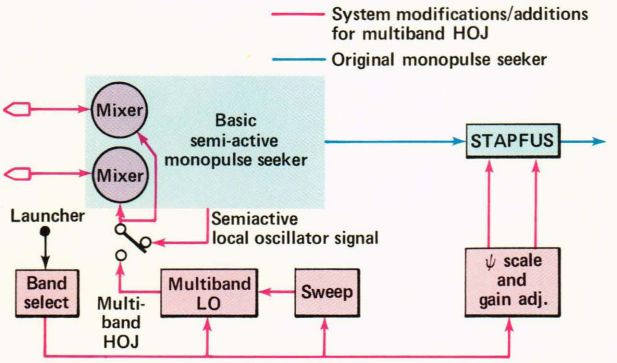


Figure 17 — The multiband HOJ system was basically an expansion of the semiactive monopulse homing system. The microwave portions of the original system were changed to provide the desired wideband operation. Frequency selection (typically 30 or 200 megahertz bandwidth) was by digital message prior to launch. Conventional semiactive homing could be activated in flight.

involved new, wideband antennas and microwave mixers and the addition of a wideband local oscillator. (The original local oscillator was used for semiactive homing.) A missile body motion ($\dot{\psi}$) and guidance gain scaler was added to adjust for the sensitivity of the interferometer to wavelength (frequency).

The multiband HOJ design was based on the simple concept that if the narrow Doppler filters of the semiactive system were excited by an intermittent signal (blinking ECM or pulse radar) at a sufficiently high rate, the output of the filters would be uninterrupted CW signals from which excellent angle information could be obtained. To ensure that the target signal could excite the Doppler filters without having to resort to the complexities of additional target recognition, acquisition, and automatic frequency control tracking circuits, the microwave local oscillator was swept at an appropriate rate over the RF band of interest. The result was a wideband seeker, the bandwidth of which was determined by the extent of the local oscillator sweep. Typically, the width of the band was either 30 or 200 megahertz. If multiple signals were present in the selected band, guidance favored the strongest signal.

The selection of the RF frequency for the multiband HOJ operation was accomplished via a digital message to the missile. Semiactive homing could be initiated in flight (if desired) in the same way as for a conventional antiair engagement.

Since it was assumed that the multiband HOJ feature would be used when target range was unknown, it was planned for the missile to fly at the fuel-conserving cruise altitude until seeker logic initiated homing. Homing always started at that altitude. For the engagement of a radar target (on land or a ship) at long range (over the horizon) but whose general location was known, a midcourse trajectory employing a terminal dive was used.

Flight hardware was fabricated, but there were no flight tests of the multimode/multiband HOJ system. In 1965, however, there were successful flight tests against radar targets at the White Sands Missile Range with Talos missiles using the same guidance concept as in the multiband HOJ system.

DEVELOPMENT OF ANTIRADIATION MISSILE GUIDANCE

Early in the Vietnam conflict, the need for an effective long-range antiradiation missile (ARM) to suppress enemy radars was evident. The Talos ARM program was authorized as a fast-reaction effort to respond to that need. The long-range capabilities and the ease with which the missile could be adapted for new missions made Talos a desirable choice for radar suppression. A feasibility demonstration flight test against an S-band radar target was successfully conducted at the White Sands Missile Range on October 26, 1965, only 35 days after initiation of the effort. Two additional guidance system designs subsequently were developed and flight tested, each progressively more sophisticated. The final design, first deployed on USS *Long Beach*, was completed in 24 months.

A unique operational concept had to be developed for ARM because it was not possible for the ship to track the target and implement missile guidance as it did for the engagement of air targets. For ARM, the target information consisting of geographic location and RF emission characteristics (frequency, pulse-repetition frequency etc.) was provided by appropriate techniques. Ship coordinates were established by means of several navigational techniques, including the Navy Navigation Satellite System. The ship then directed the missile to the vicinity of the target using the beamrider midcourse guidance. As the missile approached the target, the missile was put into a dive and the homing system was activated. Two different terminal geometries were used; one caused the missile to approach the target in an approximate 45° dive, while the other caused the missile to approach from a near-vertical dive.

The principal requirement for the ARM homing system was that it be monopulse, since the low pulse repetition frequency of some target radars was not compatible with the scan frequency used by the earlier semiactive seekers. Also, a system with a high sensitivity was desired that would provide continuous guidance on the low sidelobe levels from the target. Finally, the ARM guidance system had to be compatible with the existing Talos airframe. Modification of existing antiair warfare missiles to antiradiation missiles had to be accomplished by the relatively simple replacement of subsystem modules.

A simplified block diagram of the ARM seeker is presented in Fig. 18. The receiver used two parallel IF amplifiers (per guidance plane) with subsequent in-phase and quadrature processing. A very large instantaneous dynamic range (greater than 120 dB) was achieved by using limiting amplifiers. The differential phase shift between these amplifiers was maintained at a low level by careful attention to circuit design. Good phase tracking was attained with input peak power levels greater than 10 watts.

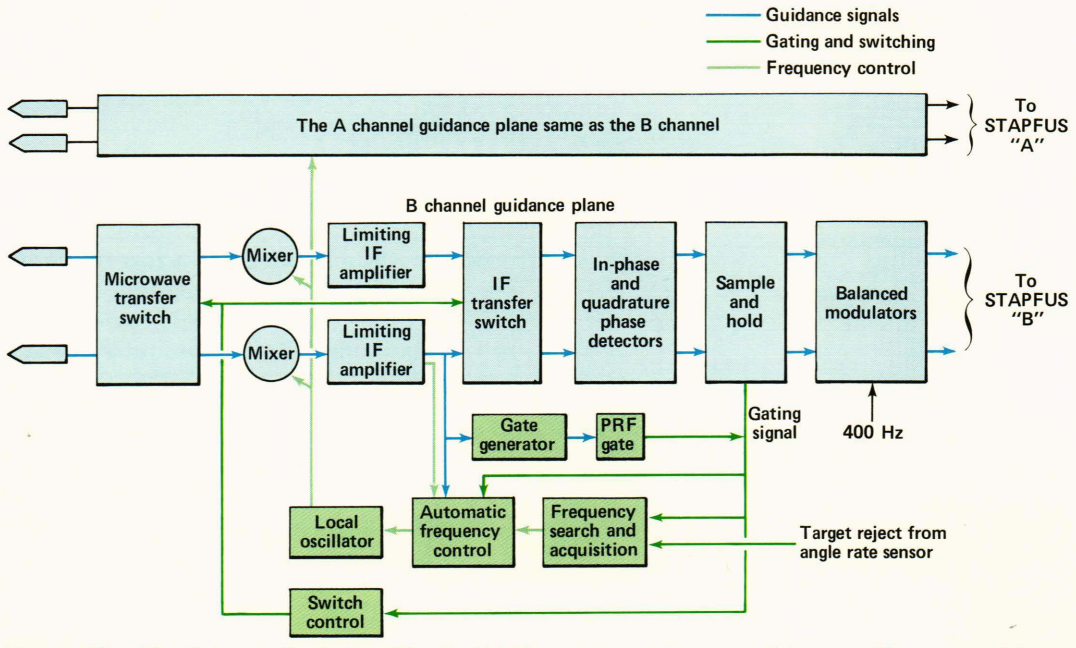


Figure 18 — The Talos Antiradiation Missile (ARM) seeker used two parallel IF amplifiers per guidance plane with subsequent in-phase and quadrature processing. A signal that satisfied the prelaunch frequency and pulse repetition frequency requirements provided the gating signal to the angle channel.

Against very-low-frequency targets (L band), the guidance error associated with as much as 10 electrical degrees differential phase shift between the receiver channels was undesirable. The error was virtually eliminated with the addition of microwave and IF transfer switches that, on a pulse-to-pulse basis, would allow radar pulses to be processed alternately through one channel and then the other. The internally generated errors would then average zero. The measured angle error arising from differential phase shift as a function of signal power level is shown in Fig. 19. The errors with and without the transfer switches operating may be seen.

In parallel with the angle channels was the acquisition and discrimination channel. The receiver was self-gating. A signal that satisfied the radiation and pulse repetition frequency requirements designated at launch would provide a gate to the angle channel. The seeker was able to discriminate between two signals if their operating frequencies differed by 3 megahertz or more. Leading-edge gating was used to minimize the effects of multipath reflections near the target. The angle phase-comparator outputs were multiplied by a 400-hertz signal to provide an amplitude-modulated signal to drive the STAPFUS resolvers.

Geometric discrimination was obtained by the seeker measuring the line-of-sight rate to the target at the time of target acquisition. The ship, via the midcourse beamriding guidance, caused the missile to

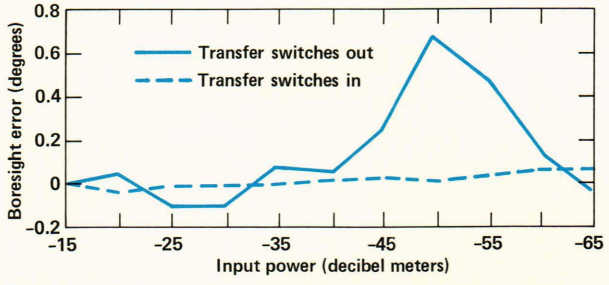


Figure 19 — Angle bias resulting from differential phase shift between the receiver channels was virtually eliminated with the use of radio frequency and of IF transfer switches that operated on a pulse-to-pulse basis.

dive toward a point that was approximately 4 miles beyond the intended target. This resulted in a missile-to-target line-of-sight rate that was in the down direction. If that downward angular rate was not detected during the target acquisition process, the signal was rejected and the seeker continued to search for another target. If the target was accepted, the missile executed a down maneuver to the target. That also enabled the missile to intercept the target at an elevation angle of approximately 90°.

Missile flight tests verified the unique design by exercising the various discriminants. Guidance accuracy was demonstrated with many direct hits (Fig. 20).

Figure 20 — A Talos ARM flight test conducted in October 1965 at White Sands Missile Range is illustrated by the sequence of pictures: (a) just before intercept of radar target, (b) impact and warhead detonation, (c) radar target after intercept. The damage mechanism is the warhead explosion plus the kinetic energy of the missile at impact.

FLETCHER C. PADDISON

THE TALOS CONTROL SYSTEM

The Talos autopilot was specifically designed to steer the ramjet missile with minimum angles of attack and to stabilize the missile in roll during the boost, midcourse, and terminal phases. The autopilot system evolved from late World War II designs by using such new components and system concepts as the hydraulic amplifying servo valve and the Sensitivity Feedback Autopilot developed by the Bumblebee Program.

The Talos wing control system was a powerful electromechanical-hydraulic system. It rotated the missile's wing surfaces to control the airframe in response to commands from the guidance system and automatically compensated for changes in aerodynamic sensitivity and stability associated with the considerable changes in missile speed (low subsonic to more than twice the speed of sound), altitude (sea level to more than 70,000 feet), and center of gravity (resulting from fuel consumption).

Talos was controlled by four independently movable wings mounted close to the center of gravity of the missile. Opposite pairs of wings moved together to control the missile in two orthogonal control planes (see Fig. 1). The missile was accelerated laterally and/or up and down when wings were deflected since the wings provided most of the missile lift. The control surfaces were sized to produce lateral accelerations that exceeded 14 g for altitudes up to 40,000 feet, above which the maximum attainable acceleration decreased. The wings were moved differentially to produce torque about the missile longitudinal axis to control missile roll. Wing control, with the attendant small angles of attack, was most desirable for Talos because airflow into the ramjet engine inlet was affected adversely by large angles of attack.

The Talos control surfaces had many design virtues, one of which was the limited motion of the center of pressure with Mach number and angle of incidence allowing the selection of the axis of rotation to minimize wing hinge moment. The effectiveness of the control system was sensitive to how quickly the control surface could move to produce lift. Accordingly, the control system was designed to move the wings at a maximum rate of 170 degrees per second.

As with all missiles, Talos had body vibrational modes during flight that necessitated care in the placement of sensing instruments, in particular those used for the control system. Even then, compensation and filtering of their signals were required. Furthermore, since the control surfaces were near the center of gravity and also near a point of maximum body vibration, the control surface had to be properly mass balanced to prevent coupling or flutter.

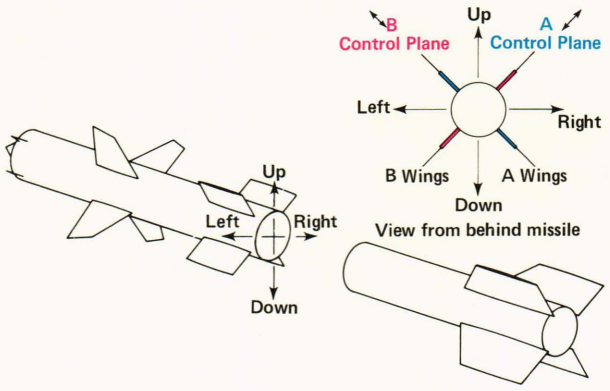


Figure 1 — The orientation of the Talos missile during all flight phases is shown. This orientation, termed "X configuration," provides maximum vertical and lateral acceleration.

The control system was functionally different for each of the three flight phases: boost, midcourse, and terminal homing. During the boost and midcourse phases, it operated as a conventional wing position system, and during the terminal phase, as an adaptive autopilot.

The servos that drove the wings were hydraulic, drawing prime power from a duct air-driven turbine. During the short early boost phase, when the air turbine was unable to supply the required hydraulic power, energy was provided by stored high-pressure nitrogen that pressurized the hydraulic system. The servos required approximately 25 horsepower.

THE BOOST-PHASE AUTOPILOT

Talos was actively stabilized during the boost phase to compensate for an aerodynamically unstable booster-missile configuration. Stabilization in the steering planes maintained the missile's orientation in space parallel to that at the time of launch. This was accomplished by command signals from a free gyroscope that had been uncaged just prior to launch. Rate gyroscopes were used in each of the two wing planes to provide damping. Figure 2 is a block diagram of the control system during the boost phase. The aerodynamic gain increased significantly during

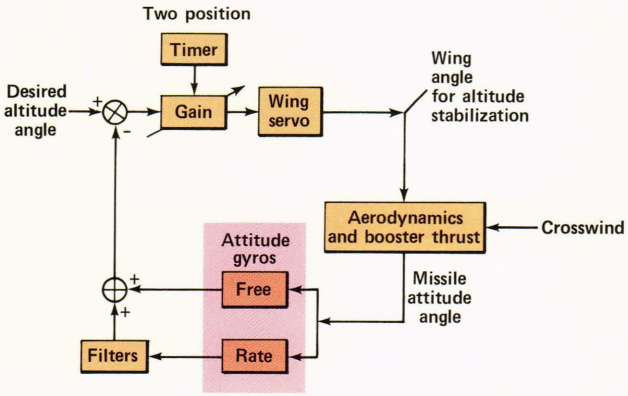


Figure 2 — The attitude control system maintained stability of the missile booster configuration during the boost phase. Two identical control channels were employed, one of which is shown. The free gyro, which was uncaged just prior to launch, provided an inertial attitude reference during the boost phase. The rate gyro was used to provide weathercock damping.

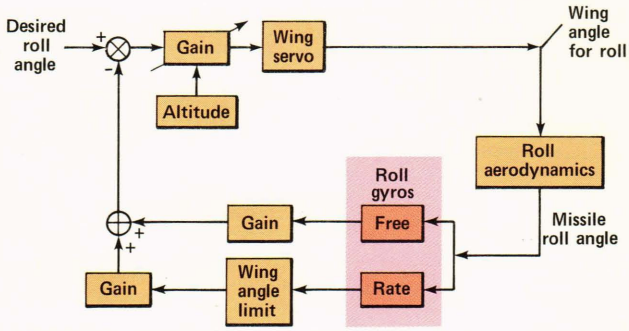


Figure 3 — Roll control was maintained during the boost and midcourse phases. The roll free gyro was uncaged at launch and provided an inertial vertical reference, while the roll rate gyro provided damping. Gain of the control loop was varied with altitude. To minimize roll-yaw-pitch coupling during the terminal phase, the roll free gyro was disconnected and a lag-lead shaping network added.

boost and, accordingly, the controller gain was reduced. This was done by a timer that reduced the gain by a factor of 2.6 at 1.75 seconds after launch. Since the effects of aerodynamic misalignments and mass unbalance, booster jet misalignment, launcher tipoff, and crosswinds during the boost phase were minimized, this boost-phase control reduced the launch dispersion and allowed the use of a relatively narrow guidance beam.

Roll control was the same for the boost phase and for the midcourse beamriding phase. Figure 3 is a block diagram of the roll system. The missile's roll position on the launcher was maintained both during the boost phase and after separation from the booster. The roll moment-of-inertia and aerodynamic characteristics during the boost phase were, of course, quite different from those during the post-separation phase. The response of the missile to roll disturbances was considerably faster after separation.

THE MIDCOURSE AUTOPILOT

Following separation from the booster, the ramjet engine was ignited. The velocity of the missile was controlled by a Mach-sensing fuel-control system, while steering was controlled by a beamrider link. During this phase, the guidance radar was programmed by target position, missile range, and previously determined parameters, all of which caused the missile to fly a trajectory that properly positioned it to begin the terminal phase.

After separation from the booster, the missile was aerodynamically stable, and control was switched from the attitude stabilization mode to a midcourse beamriding mode. An error signal, proportional to the angular off-beam error, was generated by the beamrider receiver (Fig. 4) and resolved into orthogonal components that were fed to the appropriate steering channels.

The autopilot was designed to respond to commands directing the missile to maintain its position in the guidance beam. Response was as rapid as possible without overshooting the desired position or exciting the missile's natural tendency to oscillate about its center of gravity (called weathercock oscillation). The autopilot response time varied with altitude. However, the character of the response was maintained essentially the same by programming autopilot sensitivity with altitude. Altitude was measured by a series of reliable and accurate switches that sensed the ambient static pressure. Compensation for velocity was not required since the flight Mach number was controlled. A gravity bias was used to compensate for gravity so that the missile would not fly below the center of the guidance beam as a result of gravitational force.

THE TERMINAL PHASE (HOMING)

After the midcourse phase had placed the missile into a favorable position relative to the target, a signal from the guidance transmitter activated the terminal phase of guidance. Target acquisition was normally completed soon enough after activation to permit at least 10 seconds of homing before intercept. Although 10 seconds seems a short time, it was adequate to remove missile heading errors and compensate for target maneuvers. To achieve this, the autopilot compared the requested lateral acceleration and the actual achieved acceleration produced by the control surfaces, and adjusted the internal gain of the autopilot to maintain optimum response. This "sensitivity feedback system" replaced the pressure-activated gain control used in midcourse. The block diagram for the terminal phase (homing) is shown in Fig. 5.

During the homing phase, it was desirable to rate-stabilize the missile in roll to eliminate roll-yaw-pitch coupling. Accordingly, the free gyro was not used, but control was referenced to a roll rate gyroscope to minimize the rate of roll.

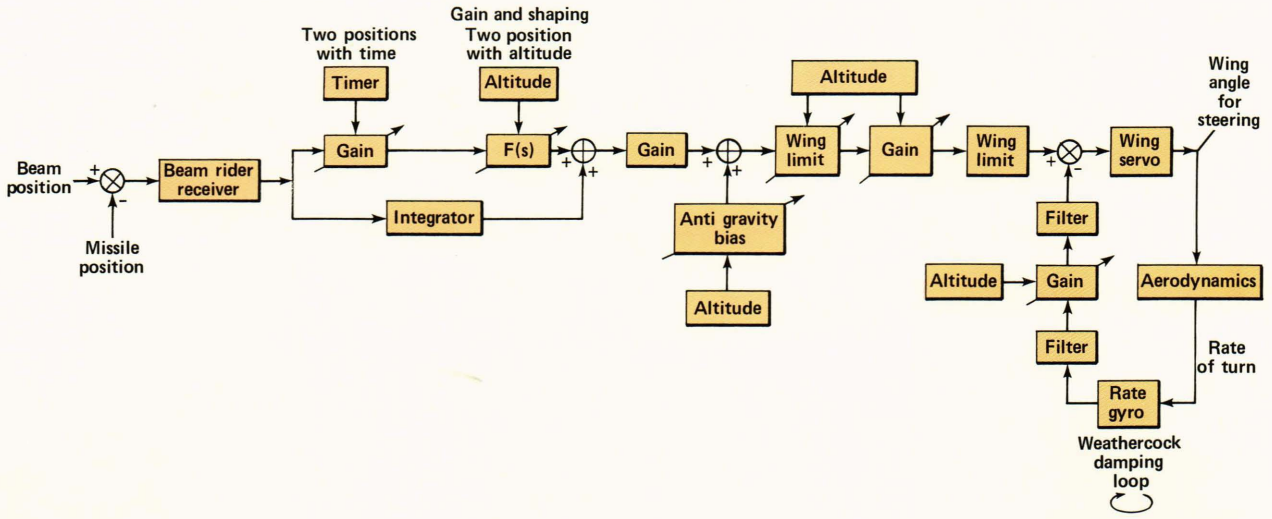


Figure 4 — Midcourse steering was controlled by a beamrider link. The beamrider receiver outputs were converted to wing commands for each control plane. These outputs were corrected for beam divergence and gravity bias by the control system. Loop gain was varied with altitude. Only one steering plane is shown.

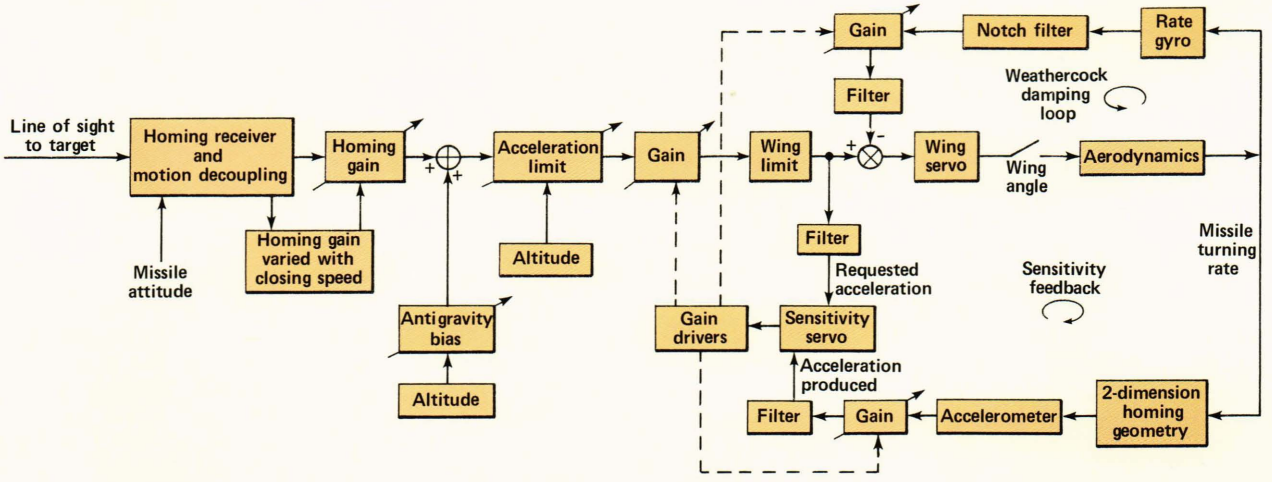


Figure 5 — Terminal steering placed the missile on a collision course by minimizing the rotation rate of the line of sight to the target. This figure shows the steering channel for one control plane. Line-of-sight rates, provided by the seeker, were converted to acceleration commands by the control system, which used the comparison of requested and achieved accelerations to adjust the gain of the autopilot and maintain optimum response. This "sensitivity feedback system" automatically compensated for changes in altitude and speed.

SUMMARY

In retrospect, the initial Talos autopilot system was an extension of World War II designs. These early systems required that the gain of the autopilot be adjusted as a function of altitude and Mach number, and programmed with time to compensate for changes in missile center of gravity as a result of fuel expenditure. The sensitivity feedback system improved the performance of the autopilot and eliminated the necessity for air density and Mach number changes to autopilot sensitivity. Talos was the first to use this sensitivity feedback design.

The outstanding performance of the Talos autopilot, despite its relative simplicity, was the result of developments in both system and component design. Many electronic, hydraulic, and electromechanical components, including end-instruments, were developed as part of the Bumblebee Program. These subsystems, components, and overall system concepts have since been used in many high-performance missiles and aircraft.

CHARLES R. BROWN and CHARLES F. MEYER

THE TALOS CONTINUOUS-ROD WARHEAD

INTRODUCTION

The warhead developed by APL for the Unified Talos (SAM-N-6c1) missile was a significant milestone in ordnance technology. Performance objectives were achieved with a configuration in which a double layer of steel rods, welded at the ends to form hinge joints, was accelerated by the detonation of a cast explosive. Structural damage to the target was achieved by the impact of the steel rods projected at high velocity in an expanding circular pattern (Fig. 1). This was shown to be a highly effective counter to any manned aircraft, such as a heavy bomber. An accurate fuze was employed to control burst position so that the rods would strike the target.

The continuous-rod warhead evolved from consideration of the lethality of chunky fragmentation devices and their inability to inflict a decisive kill on a manned aircraft. The optimum fragment velocity for effective target penetration was shown to be considerably higher than that of about 3000 feet per second from an antiaircraft shell. Considerable improvement in lethality was observed when the chunky fragments from a 3-inch/50 shell were replaced by small discrete rods.

A quick, decisive kill was shown to be feasible when a long rod sufficiently damaged the aircraft structure so that failure resulted from normal aerodynamic flight loads. Ordinary fragments, while adequate for damaging vital components, cannot produce such structural failure. The continuous-rod concept was born in 1952 with the suggestion that the rods be connected end to end, thereby providing the capability of inflicting a continuous "line" of structural damage over the target surface.

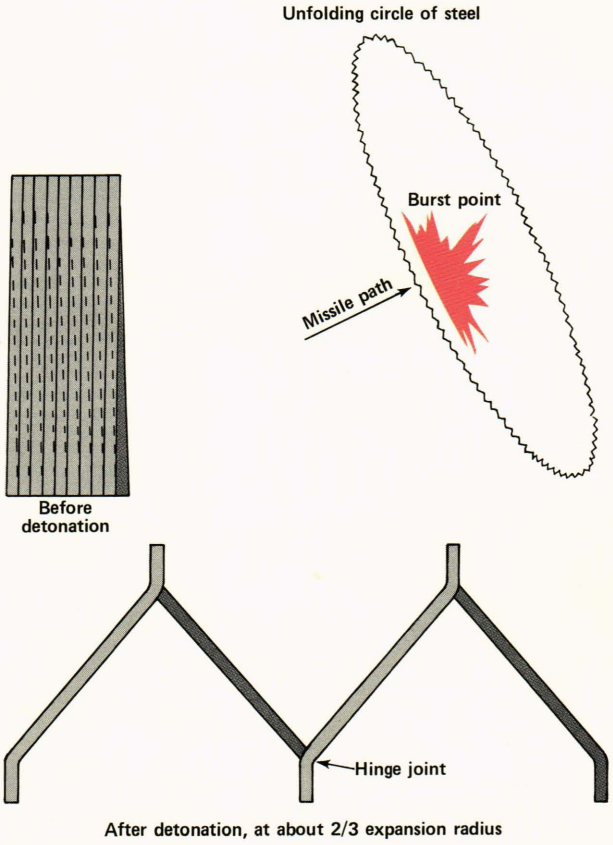


Figure 1 — The continuous-rod warhead was designed to produce an expanding zigzag ring of connected rods. The rod structure expanded like a folding rule.

WARHEAD DESCRIPTION

The Mk 46 continuous-rod warhead, developed for the Unified Talos 6c1, is shown schematically in Fig. 2. Each pair of a double layer of 0.25-inch square rods, 19.25 inches long, was resistance welded at the ends to form a hinge joint. The rods were welded together in two flat sections that were connected by two heli-arc welds after assembly on the cylindrical surface. At the explosive-rod interface, two filter layers — a 0.062-inch layer of steel and a 0.025 inch layer of lead — helped to reduce the explosive shock effect on the steel rods, the steel filter being part of the basic warhead structure. Structural rigidity was achieved by a 0.035-inch steel stress skin over the rods; both rods and stress skin were welded to steel end rings.

Detonation of the explosive composition, nominally 25% RDX and 75% TNT (cyclotol), was centrally

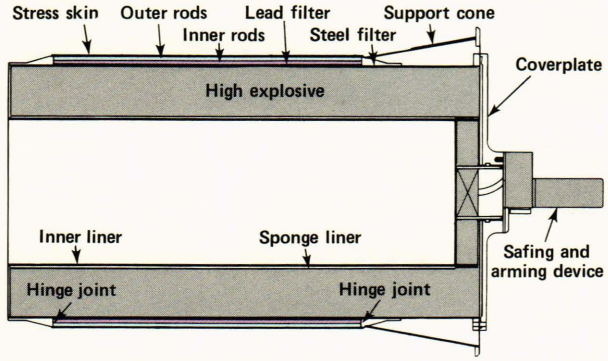


Figure 2 — The Unified Talos 6c1 Mk 46 warhead was a hollow cylindrical structure. Quarter-inch rods arranged in a double layer and surrounding the explosive charge were welded at the ends to form hinge joints. At the explosive/rod interface, two filter layers — a 0.062-inch layer of steel and a 0.025-inch layer of lead — helped reduce the explosive effect on the steel rods.

initiated at the aft end where the detonator and booster were part of the overall safing and arming assembly. A silicone sponge liner was used on the approximately 8.7-inch outer diameter steel inner liner to prevent cracking from shrinkage of the explosive caused by cooling in the casting process.

The overall weight of the warhead was about 465 pounds, and the explosive load was about 225 pounds. Warhead length, not including the end plate and the safing and arming device, was about 29.5 inches and the diameter of the section comprising the rod assembly was about 16.8 inches.

The location of the warhead within the missile structure is shown in Fig. 3. The blowthrough area is the section that has the most effect on warhead performance. Lockfoam was used between the warhead and the inner-body cowl as a cushion to prevent the rods from damaging the magnesium cowl. Coaxial cables, pitot tubes, and their fairings were designed for the most practical, circumferentially uniform distribution of mass to minimize rod breakup.

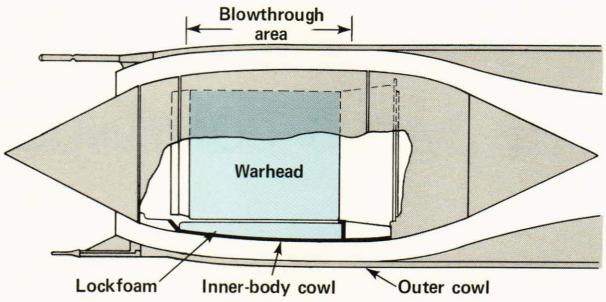


Figure 3 — The missile and warhead structure was designed to place the warhead in the inner body of the multiple-shock diffuser. Lockfoam was used between the warhead and inner-body cowl as a cushion to prevent the rods from damaging the magnesium cowl. Coaxial cables, pitot tubes, and their fairings were distributed to minimize rod breakup.

DEVELOPMENT AND PERFORMANCE OF THE TALOS WARHEAD

Problems solved during the development of the Mk 46 warhead were associated with preventing rod deformation, controlling initial rod motion so that a nearly unbroken rod pattern persisted to the maximum radius, and producing rod velocities high enough to inflict structural damage on the target.

Fastax camera coverage of static testing of the warhead in an arena of steel witness plates (Fig. 4) provided valuable performance data on rod continuity, rod pattern, and velocity. Extensive recovery of sample rod strands yielded vital information on hinge opening and the metallurgical properties of the rods.

The missile structure had a strong influence on warhead performance. About 30% of the kinetic energy of the rods was lost in the process of blowing through the substantial missile structure. The initial velocity was reduced from about 5300 to about 4600 feet per second, a useful speed. However, rod continuity seemed to be somewhat improved because gapping between inner and outer rod layers was reduced.

The maximum radius of continuity was 90 feet. Ideally the rods would produce a uniform "saw-

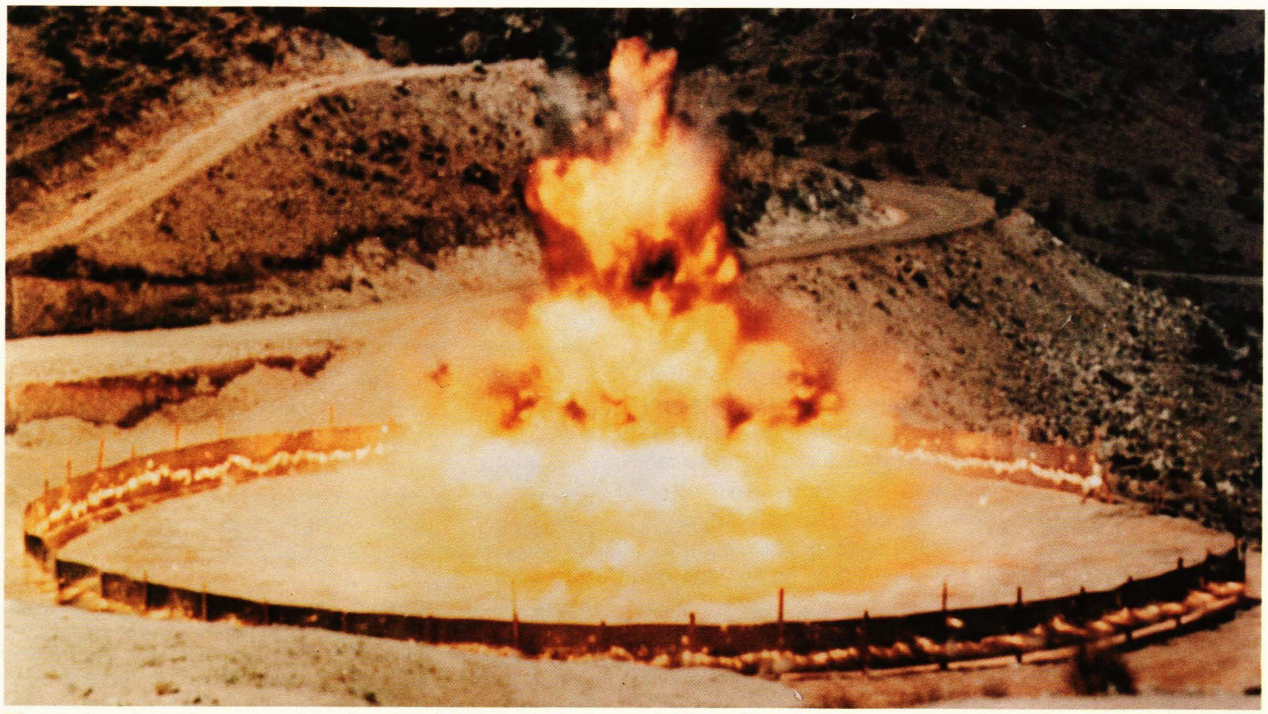


Figure 4 — A continuous-rod warhead test demonstrated an unbroken ring of continuous rods. This photograph shows the continuous rods striking steel target panels located near the maximum possible continuity radius.

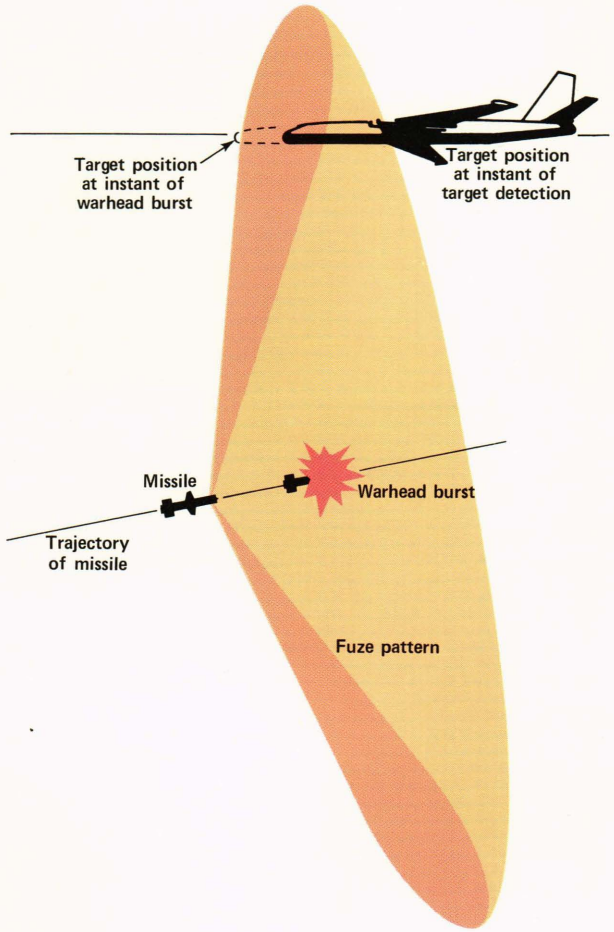


Figure 5 — Warhead burst position was controlled to obtain maximum effectiveness of the continuous-rod warhead. The target was detected by a short-pulse range-gated radar having a fixed-angle antenna pattern. The time delay from detection to burst was controlled by the missile-to-target closing speed.

tooth'' pattern during expansion in such a way that all rods would break simultaneously at the hinges when the maximum radius was reached. In practice, the expansion was not uniform, and some hinges would always break prematurely. Typical continuity performance was 100% out to a radius of 60 feet, with a degradation to 90% at 90 feet.

The hinge weld played an important role in preventing excessive premature rod breakage. It consisted of a strong weld in a primary region and a weaker weld in a secondary region. Progressive failure of the secondary weld helped to control the bending radius during the expansion process, while the primary weld remained intact.

FUZE

The final fuze version (Mk 52), designed by the Naval Ordnance Laboratory, Corona, Calif., was a short-pulse-radar, range-gated device having a fixed-angle radiation pattern (Fig. 5). A sea tracking gate

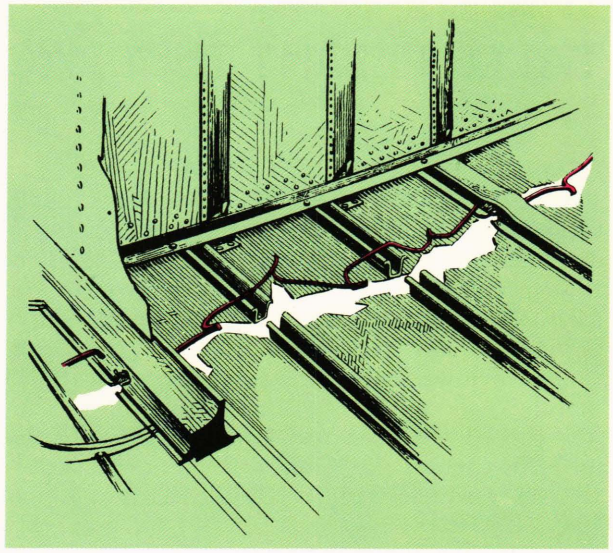


Figure 6 — Cutting action of the rods across the target surface could lead to structural failure and therefore produce a quick kill.

was included to prevent premature firing on the sea when intercepting very-low-altitude targets. The warhead was fired by a signal originating from a valid target detection or by fuze-on-jamming action. The missile-to-target closing rate controlled the time delay of the burst so that optimum effectiveness was achieved.

Analyses of time delay requirements were performed for a variety of targets, intercept-approach aspects, and altitudes. Suitable constants for the time-delay equation were thus derived for optimizing hit probability.

TARGET DAMAGE

The nearly continuous cutting action of the rods across the target surface could lead to structural failure and therefore produce a quick kill. Complete severence of the structure was not necessary. For example, if the skin and stringers of a wing were severed and the heavy spars damaged, the wing could fail under a 1g flight load (Fig. 6).

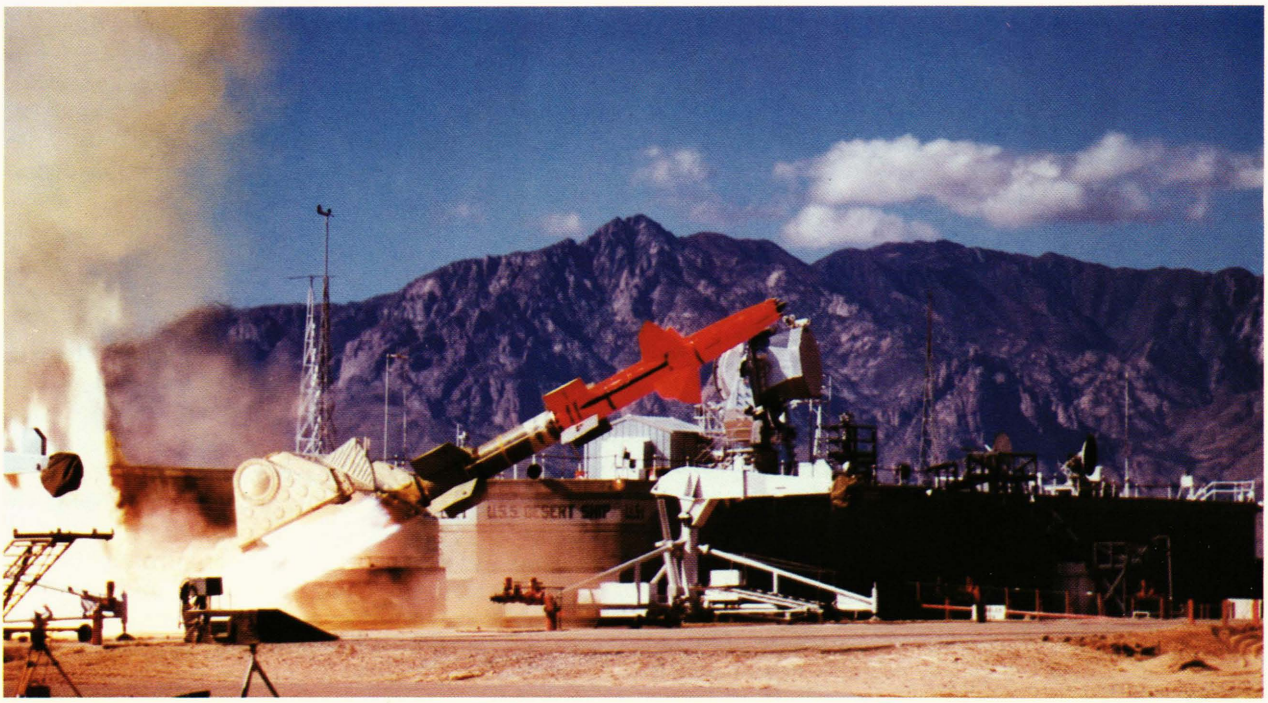
Structural damage by the impact of rods required a sufficient mass, high impact velocity, and a continuous strand of unbroken rods. For quarter-inch rods, a minimum striking velocity of about 3500 feet per second was necessary to produce structural damage to most aircraft.

Experiments showed that a rod that struck a thin target edge-on tended to break into two pieces during the damaging process. The amount of damage produced greatly depended upon the ability of the rod to resist being pulled apart. On the other hand, a rod striking a target whose thickness was much larger than the rod's thickness was broken into three pieces, the center portion contributing the most to the damage.

TALOS FLIGHT TEST FACILITIES

From February to December 1945, flight tests to support propulsion and aerodynamic studies for the development of Talos were conducted at Island Beach, N.J. Activities were then transferred to Fort Miles, Del., pending the opening of the Bureau of Ordnance's east coast range at Camp Davis, N.C. Camp Davis was deactivated in 1948 because of lack of funds, and all flight testing in support of Talos was shifted to the Naval Ordnance Test Station (NOTS), China Lake, Calif. Testing of steering test vehicles was undertaken at NOTS as early as August 1945.

Most early flight tests in support of the development of the guidance system were conducted at NOTS. Large (18-inch diameter) ramjet test vehicles were also tested there during the period from 1946 to 1950. When test requirements exceeded the available range at NOTS, the testing was shifted to White Sands Proving Ground, now White Sands Missile Range (WSMR). As time passed and the missile guidance system was in the final stages of development, shipboard prototype equipments were assembled at WSMR into a weapon control complex that was commissioned USS *Desert Ship*. That facility made it possible to test missile system improvements and the compatibility of the missile with the prototype shipboard equipment. *Desert Ship* supported development of the Talos Weapon Control System until about 1965.



A First Tactical Talos leaves its launcher at USS *Desert Ship*, White Sands Missile Range, N.M. (This is one of hundreds of fine technical photographs taken by the late Clyde T. Holliday during his long and distinguished career at APL.)

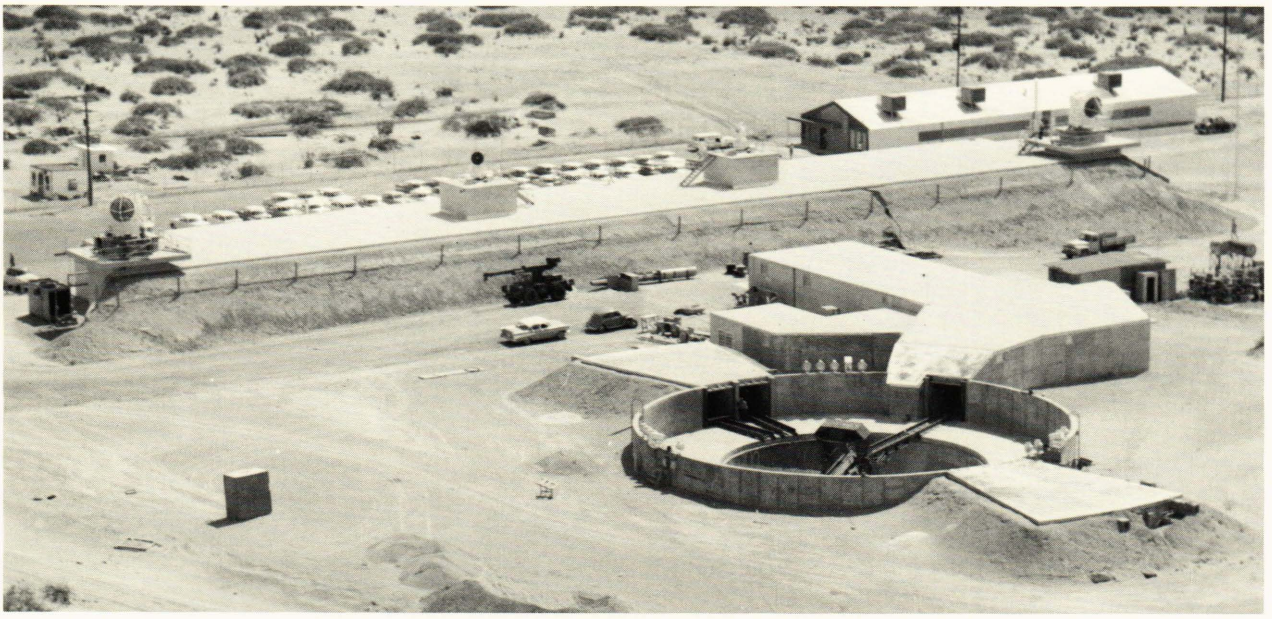
THE TALOS LAND SYSTEM

The Talos missile was in a state of advanced development and ready for final production engineering in the early 1950's, although it would be several years more before the first Talos ship was ready for a load of missiles. The Talos missile represented such a considerable advance in the state of the art that it attracted the attention of the Air Force, which was interested at the time in the defense of Strategic Air Command bases. A design proposal of such a land-based system was prepared by the Laboratory and, following approval by the Air Force, a contract was let by the Bureau of Ordnance to RCA, Moorestown (N.J.) Division, to put together a land-based weapon system.

The RCA Talos Land System was the most advanced air defense system developed up to that time and also, because of automatic self-testing and fault identification, one of the most reliable. The basic components of the system were two C-band monopulse radars to track and illuminate targets, four C-band guidance radars to support midcourse guidance, a launching system that used a round-house arrangement for storage of missiles, and digital computers to control and monitor the system operations. It was engineered into an operating entity, ready for test and evaluation, in only 18 months. The figure shows the system installed in its own building at White Sands Missile Range, N.M.

The evaluation of the system demonstrated many firsts, including the completely automatic hands-off operation of an antiair warfare system, from target designation through target intercept. Further, the Land System demonstrated the concept of multiplexing, where several missiles are in flight simultaneously and the illuminator is directed from one target to the next at the right time for each missile's terminal phase. In addition, system capabilities were under study to use the nuclear warhead version of Talos as a last-ditch defense against ICBM's. No tests were ever carried out, but the concept has now resurfaced, some 30 years later, in the attempt to achieve survivability of missile silos.

The Talos Land System evoked a prolonged controversy between the Air Force and the Army, which was supporting the Nike Hercules system. The end of that evaluation, in the fall of 1956, was a jurisdictional decision by the Senate Armed Services Committee. It awarded the responsibility for land-based missiles with a range of up to 100 nautical miles to the Army and responsibility for missiles beyond that range to the Air Force. The Talos Land System, just starting its detailed evaluation and demonstration, was placed under the aegis of the Army, which then took over the evaluation; afterward, the system was disassembled. RCA continued to develop the Talos Land System's fire control radars, which had been under development as part of the Bumblebee Program and which later became the well-known FPS-16 Instrumentation Radars.



The Talos Land System, installed at White Sands Missile Range, included two C-band monopulse radars, two C-band guidance radars, a launching system, and a partial magazine for six missiles.

ELMER D. ROBINSON

THE TALOS SHIP SYSTEM

The Long Range Talos missile placed requirements on the ship system that were beyond the state of the art during the entire lifetime of the Talos Weapon System. However, valuable lessons were learned that affected the development of later systems. The evolution of the ship system proved that patchwork techniques could not be used to satisfy tactical needs.

The initial concept of the Talos Weapon System was established in 1952 and included antiair, antiship, and shore bombardment capabilities. There were two types of missile, each having intercept ranges up to 50 nautical miles. One missile carried a command-detonated nuclear warhead, and the other, a proximity-fuze-detonated continuous-rod warhead. The nuclear warhead missile rode a programmed guidance radar beam to the vicinity of the target, where it was detonated by a command from the ship. The missile with the continuous-rod warhead employed midcourse beamriding and terminal semiactive homing.

As would be expected, the Talos fire control system was directed from the ship's weapon control center. That center processed search radar data, provided selected coordinate data to the fire control radar, ordered loading of the missile launcher, and controlled missile firing.

To control the missile in flight, a continuous measure of target and missile position was necessary. There were three major subsystems: a target tracking radar to measure target position and to illuminate the target, a guidance radar for beamriding and missile range measurements, and a computer to generate angle-rate signals for positioning the guidance beam and activating the terminal homing system. Three types of trajectory were employed by Talos (Fig. 1).

Talos was constantly improved during the course of the Program. Improvements in missile capabilities became a primary driving force in establishing ship system requirements. Extending the maximum missile range, for example, forced the use of a new generation of search and target acquisition radars. The shift to continuous wave (CW) homing required the installation of CW illuminators. The state of the art was constantly being applied to improve the weapon system. A detailed description of the Talos ship system depended on the ship and the date.

The typical Talos system (Fig. 2) contained:

- Search radars that were used to detect targets and provide position data to the weapon control system;
- A weapon control system that made target assignments to the fire control system, ordered loading of missile launchers, fired missiles, and linked defense responses with Fleet units;
- A fire control computer that interfaced all elements of Talos to control the missile in flight;
- A fire control radar that accurately tracked the designated target and provided illumination for semiactive homing;
- A missile guidance radar that acted as a command link to the missile.

TALOS SHIP INSTALLATIONS

USS *Galveston* (CLG-3) was designated as the first ship to receive Talos missiles and underwent an austere conversion to accommodate the missile. The aft main gun battery and seaplane catapults were removed. A dual-rail missile launcher was installed. The ship's structure was modified to include a missile magazine, a missile handling area, and barbettes for the target tracking and missile guidance radars. Spaces for the radar consoles, the fire control computers, and a weapon control system were included. Missiles were loaded on the launcher by extendable and retractable overhead rails. The fire control system was a functional copy of the ground system used during development testing at White Sands Missile Range. Two fire control channels, consisting of

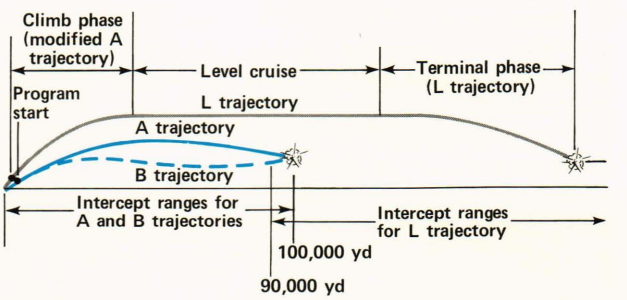


Figure 1 — Talos flight trajectory types depended on the range to the target and the electronic countermeasures environment. The A trajectory was medium range and approximated a circular arc. The B trajectory, also medium range, closed the beams earlier to reduce susceptibility to enemy countermeasures. The long-range L trajectory was used for intercepts at greater than 90,000 yards.

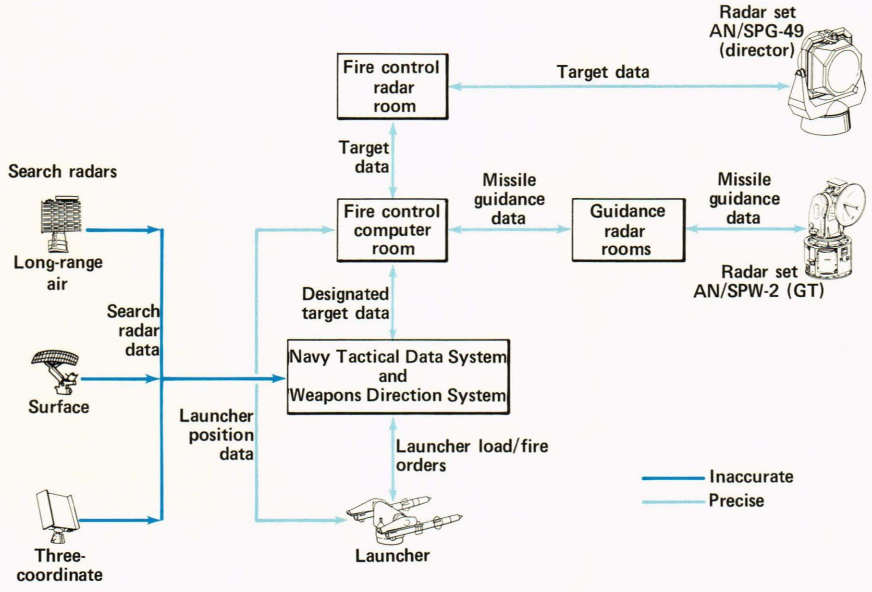


Figure 2 — Typical Talos Weapon System.

tracking radars, computer channels, and guidance radars, were required to support the dual-rail launcher (Fig. 3).

The Combat Information Center in *Galveston* was modified for mounting a television camera above a master plan position indicator and for the installation of two repeater displays. These formed the link between the Combat Information Center and Talos. Information could also be transferred by the use of grease pencils on the televised displays.

The Talos Weapon Control System provided manual tracking of up to six targets and the designation of any two of them to fire control channels. Little thought was given in the early days to a large number of targets, adverse environments (jamming), designation accuracies, and system reaction times.

Shortly after authorization of the *Galveston* conversion, two additional ships were authorized — USS *Little Rock* (CLG-4) and USS *Oklahoma City* (CLG-5). These ship systems were very nearly identical with the system on *Galveston*. The initial installation in these three light cruisers supported the short-range version of the missile (50 nautical miles).

Introduction of the long-range missile (100 nautical miles), and later the CW seeker, imposed changes in the ship system. These changes involved increasing the tracking range of the fire control radar, increasing the instrumented range of the fire control computer channels, and adding a low-noise-level, high-power CW target illuminator. Also required were a computation of the closing velocity between missile and target and the relaying of this information to the missile.

The long-range missiles focused attention on the need for long-range target detection and rapid handling of multiple targets in adverse sea, land, and weather clutter and heavy countermeasure environments. Threat studies showed that the search radars and weapon control system in the light cruisers were inadequate to support Talos in a heavy threat or jamming environment.

Figure 3 — USS *Galveston* (CLG-3) was designated as the first ship to receive Talos missiles. Two of the first tactical Talos missile types, SAM-N-6b and SAM-N-6bW, are shown on the launcher.

The first chance to install an improved ship system occurred with the authorization to convert USS *Long Beach* (CGN-9) to a Talos ship. This first nuclear-powered cruiser had powerful long-range search and acquisition radars that used state-of-the-art, fixed-array, electrically steerable beams and a new Weapon Control System capable of rate-aided manual tracking of up to 24 targets. Digital computer technology

Table 1 — The Talos ships.

Ship	*Commissioned*	*Armament*
USS *Galveston* (CLG-3)	May 1958	46 Talos missiles 6-inch triple-barrel gun 5-inch dual-purpose guns
USS *Little Rock* (CLG-4)	Jun 1960	Same as CLG-3 except for the number of guns
USS *Oklahoma City* (CLG-5)	Sep 1960	Same as CLG-3 except for the number of guns
USS *Long Beach* (CGN-9)	Sep 1961	52 Talos missiles 240 Terrier missiles 5-inch twin-barrel guns
USS *Albany* (CG-10)	Nov 1962	104 Talos missiles 80 Tartar missiles 5-inch twin-barrel guns
USS *Columbus* (CG-12)	Dec 1962	Same as CG-10
USS *Chicago* (CG-11)	May 1964	Same as CG-10

using hard-wired techniques was used for the first time in the Fleet. Solid-state devices were used in the analog fire control computers to improve their reliability. The nuclear-powered cruiser was the first Talos ship to employ the Naval Tactical Data System for ship-to-ship and ship-to-air communications.

The next chance to install an improved ship system came with the authorization for conversion of three heavy cruisers to carry Talos and Tartar. The seven Talos ships, their commissioning dates, and armaments are listed in Table 1.

SEARCH RADARS

Three basic types of search radar were used on the Talos light and heavy cruisers: a short-range surface search radar, a longer-range radar for range and bearing data, and a long-range air search radar for range, bearing, and target height data. Radar video and timing signals were sent to the Combat Information Center in all the ships and to the Weapon Control System in the heavy cruisers.

WEAPON CONTROL SYSTEM

The Talos Weapon Control System served several purposes: classification of targets based on search radar data, assignment of targets to fire-control channels, display of repeat-back data from the fire control radars, determination of open fire and intercept ranges, evaluation of the booster splash point and firing cutout zones, selection of the missile type to be used, assignment and loading of the missile launchers, and firing of the missiles.

The weapon direction equipment in the light cruisers contained two large displays of televised radar scopes and a bank of lights for indicating the status of the weapon system. Data written on the televised radar scopes would appear on the displays. Four smaller repeaters were installed — two in the Weapon Control Center and two in the Combat Information Center. Two target engagement consoles interfaced with the main displays via a symbol generator. Six targets could be processed simultaneously. One target could be designated to each of the two fire control channels and one to the gun system. A missile firing panel enabled missiles to be selected, loaded, and fired. It contained a display of surface radar data and superimposed booster splash point and firing cutout zones. A height storage console interfaced the system with three-dimensional search radars.

At the time that a weapon control system was selected for the nuclear and heavy cruisers, digital systems were being developed and more severe threats were being recognized. A hard-wired digital computer, representing the state of the art at that time, was selected for the Weapon Control System. Two target entry consoles were installed for assigning targets to track consoles and for monitoring the weapon systems (Talos and Terrier in the nuclear cruiser and Talos and Tartar in the three heavy cruisers). Six target tracking consoles were installed, each of which could process four targets. The program for processing data for as many as 24 targets was stored and handled in hard-wired magnetic core memory. Frequent manual entries were required to maintain accurate tracks. Two director assignment consoles interfaced the Weapon Direction System with the fire control systems. Four launcher assignment consoles interfaced the system with the missile launchers — two for Talos and two for Tartar.

The hard-wired digital computer proved to be inflexible and expensive to change. It had a high failure rate and long diagnostic and repair times. The solution of these problems appeared to be the replacement of the entire system with a general purpose digital computer and general purpose consoles. These equipments became available too late in the lifetime of the cruisers to warrant their installation.

FIRE CONTROL RADARS

The Talos missile required an automatic tracking radar that was powerful and accurate, with an acquisition capability to cope with target designation errors from search radar data. In 1949, a survey of available radars resulted in the selection of a gun-laying radar that could be adapted to Talos. It consisted of two integrated radars: a scanning acquisition radar and a monopulse tracking radar (Fig. 4). The antenna director had three degrees of freedom: train, elevation, and traverse. The traverse member permitted the tracking of high-speed crossing targets and gave the radar a track-overhead capability. All of the microwave equipment, antenna control electronics, and high-voltage power supplies were mounted within the director. This location made the radar difficult to service at night or during inclement weather. The directors were mounted on barbettes that extended to the keel of the ship for alignment stability. Two operator consoles were mounted below decks — an acquisition console having a unique five-plane display, which gave a synthetic three-dimensional display of the volume of space containing the target, and a tracking console with a range scope display and a plan position display.

The radar was modified at the same time the long-range missiles were introduced, to increase range and to include a high-power CW target illuminator operating through an indexed target-acquisition antenna system. It became the highest-powered, most accurate radar in the Fleet until the digitally controlled pulse Doppler fire control radar for Tartar was introduced in the late 1960's.

Over the years, numerous modifications were proposed and tested to improve radar performance at low elevation angles, for targets in clutter, for fading targets, and for targets screened by countermeasures. Some of these modifications included pulse compression, fade-coast mode, low-elevation-angle mode, track-on-jamming capability, alarm gate for chaff, and digital range gate processors.

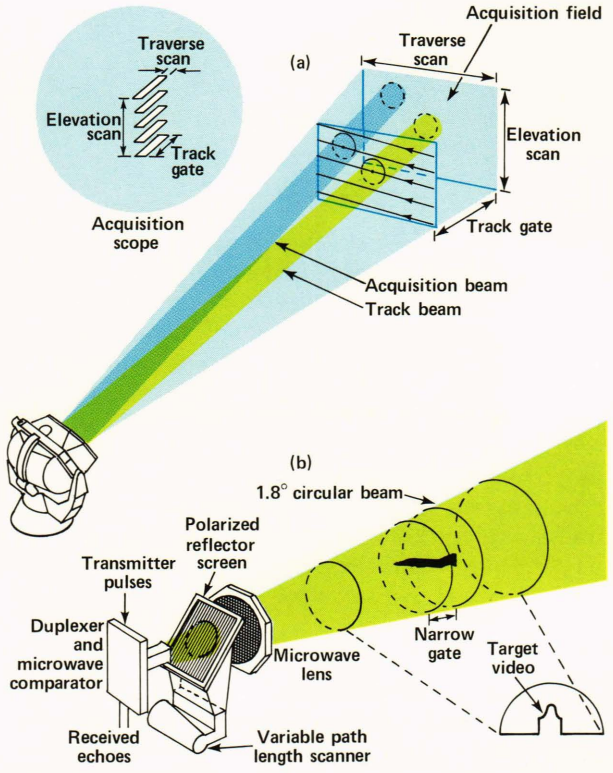


Figure 4 — The Talos fire control radar consisted of two integrated radar systems using a common microwave lens: (a) The acquisition system was scanned by a motor-driven polarized reflector grid and a scanning feed. (b) The tracking radar system, polarized at 90° from the acquisition system, operated through the transparent reflector grid.

FIRE CONTROL COMPUTERS

The fire control computers for Talos were an extension of gun fire control technology of the early 1950's. They were vacuum tube, electromechanical devices performing three-dimensional coordinate conversions in real time and solving both linear and nonlinear equations. These computers implemented the following tasks: target designation; target tracking; launcher assignment and guidance radar control; booster splash point and firing cutout zone calculations; and missile firing and beam programming for antiair, antiship, shore bombardment, and home-on-radiation missions. The computers were originally designed to support the short-range missiles and were later modified to support the long-range missiles.

The analog computers were subject to long settling times and inaccuracies caused by drifting. The drifts were not detectable without comprehensive tests and analysis. As a result, extensive test and adjustment procedures were developed. A high failure rate increased the maintenance burden and system downtime.

The fire control computers for the nuclear and heavy cruisers used solid-state analog technology in the 1958-59 era. However, they suffered from the same problems experienced with the earlier computers — long settling times and inaccuracies.

The problems with the analog computers led to the first studies of digital fire control systems in 1956. The studies, however, were aimed at two additional heavy cruisers and not at existing ships. Cancellation of the cruiser shipbuilding program halted the studies of digital systems until 1961, when APL-built analog-to-digital conversion equipment became available for interfacing with general purpose computers. The operational capability for digital control of guidance radars was demonstrated in 1964. These demonstrations led to evaluation of a digital fire control computer system in USS *Albany* (CG-10) in late 1964 and early 1965. A Univac Model 1218 computer was selected; it became known as the military Mk 152 digital computer.

The development of digital range data processors for the Talos target tracking and guidance radars was paced with the development of the digital fire control

computers. The first conversion to a digital system took place in *Albany* in 1966. Conversion of the nuclear-powered *Long Beach* and of USS *Chicago* (CG-11) soon followed. The three light cruisers and USS *Columbus* (CG-12) were retired before conversion took place.

MISSILE GUIDANCE RADAR

By the end of World War II, several target-tracking fire control radars existed that used conical scanning antenna feeds and time-domain signal processing for tracking targets automatically. Beamriding missiles became an extension of that technology by relocating the radar receiver in the missile and using the output to control the missile.

The missile guidance radar selected for Talos employed a 4°-wide pencil beam that was offset 2° from boresight and nutated about it at a 30-hertz rate. The train and elevation angles in the guidance radar could be controlled manually during collimation testing or remotely by the fire control computer during beam programming. The pulse repetition rate of the radar was frequency modulated sinusoidally at a 30-hertz rate and with a phase related to a stable platform so as to remove the effects on missile attitude of ships' roll and pitch. The frequency modulation provided the missile with a phase reference with which to compare the phase of amplitude modulation resulting from being off boresight. The result of the phase comparison was used to steer the missile in the required direction to follow the boresight line during guidance beam programming.

Instead of a single pulse in conventional radars, the guidance radar used a group of pulses that could be time coded to identify a particular missile with a particular guidance radar and to convey commands to the missile. The coded pulse group also triggered a transponder in the missile to enhance missile tracking by the guidance radar.

The guidance radar for Talos used 1950's technology, and no major modifications were made until digital range data processors were developed in 1966. During its lifetime, several minor changes were made to decrease the receiver noise figure for longer range beacon tracking, improve the settling time of the range tracking output after beacon lock-on, and improve the guidance radar operability and maintainability.

MISSILE LAUNCHING AND HANDLING SYSTEM

Missile magazines and handling areas were installed in the aft end of the light cruisers and the nuclear-powered cruiser. Magazines and handling areas were installed in both ends of the heavy cruisers. A bookkeeping system was incorporated for locating and calling out missiles with continuous-rod or nuclear warheads. Later on, the bookkeeping system was modified to include the location of missiles configured for home-on-radiation missions. In the heavy cruisers, the launchers could be assigned to either the forward or aft fire control channels. Each handling area contained a battery charger and Talos tactical test equipment. The specialized test equipment could exercise the electronics and hydraulics of a missile for periodic tests to determine readiness. On-board repair of missiles could be accomplished by module replacement using on-board spares. At sea, resupply of missiles was accomplished by high-line transfer from ammunition ships. Few changes were made to the missile launching and handling systems during the lifetime of Talos.

EQUIPMENT AND SYSTEM DOCUMENTATION

The introduction of the complex Talos, Terrier, and Tartar Weapon Systems in the Fleet soon demonstrated the inadequacies of available documentation. Failure-reporting procedures were insufficient to highlight problem areas and give direction to the logistic system. Test and evaluation techniques were inadequate to determine the readiness of equipment to meet the needs of an exercise or a real engagement.

A System Operability Test was developed in 1962 to determine system capability to support a mission. This evolved into a Daily System Operability Test that included simulated missile firings and measurement of system parameters for a go/no-go condition. The Daily System Operability Test was also a training aid for maintaining the proficiency of weapon system personnel.

Signal flow diagrams known as pyramids were developed in 1963 to assist personnel in locating faults quickly. This resulted in a new type of documentation known as Improved Maintenance Plans, which evolved into a Planned Maintenance System for surface missile ships. A failure-reporting system was developed that permitted rapid determination of mean-time-between-maintenance events, mean time between failures, mean time to repair, system availability times, and demands on the logistic system.

CONCLUSION

The Talos Program motivated developments in many areas of weapon system technology. The existence of a guided missile having a tactical range in excess of 100 nautical miles most certainly advanced the state of the art in long-range target detection and target data handling. It pointed out the need for:

1. High firing rates for long-range missile systems;
2. Automatic evaluation and reaction to threats;
3. Improved counter countermeasures for radar systems; and
4. Digital computers in all areas for automation, accuracy, flexibility, and maintainability.

The Talos Weapon System provided seven cruisers with a wide-area air defense system unequaled at its time by any other guided missile system in the Navy inventory.

DONALD D. A. GRAY

THE TALOS SHIPBOARD TEST PROGRAM

At-sea tests were necessary to determine weapon system performance and evaluate proposed system improvements. The tests were conducted from combat ships and were squeezed into the ships' schedules of operational commitments.

INTRODUCTION

The basic objective of the shipboard test program was to evaluate the ability of the Talos missile and shipboard weapon system to provide an effective defense against aircraft attack. A major part of the effort dealt with the determination of missile and weapon system deficiencies and the evaluation of proposed improvements.

The test program was not formally chartered or planned, but evolved. The need started with the commissioning and technical evaluation of USS *Galveston* in 1958 and ended, some 27 projects later, on board USS *Chicago* in 1970, with a test involving the use of search radar data to control the midcourse phase of a missile flight.

The program was conducted under the direction of the Talos Project Office of the Bureau of Naval Weapons and with the assistance of the U.S. Naval Ship Weapon System Engineering Station. Other organizations participating were Bendix Aviation Corp., the missile contractor; Sperry Gyroscope Co., the fire control equipment contractor; Northern Ordnance and General Electric Co., the launching system contractors; the Naval Weapons Center, China Lake; the Naval Weapons Laboratory, Dahlgren; and Vitro Laboratories, the system integration contractors. APL's role was to plan the test projects, write the test procedures, and coordinate and supervise the test operations. Providing services and scheduling ships and aircraft were done by the Operational Test and Evaluation Force of the U.S. Navy. Analysis and reporting of test results were largely done at APL. Flight test analysis was conducted in collaboration with the Fleet Missile System Evaluation Group.

PROGRAM HIGHLIGHTS

A chronological summary of the Fleet Test Program is shown in Fig. 1. All of these tests were designed, conducted, and reported by APL, with the assistance of the Talos equipment contractors.

The first Talos cruiser, *Galveston*, was commissioned May 28, 1958, at the Philadelphia Naval Shipyard. The Technical Evaluation of the Talos weapon system started in the fall of 1958 after the ship's fitting out and shakedown period. All aspects of the Talos missile system were checked out and evaluated prior to missile firings in March 1959. This was the first use of the 50-nautical-mile Talos (XSAM-N-6b and -6bW) missiles at sea. The series of tests was followed by a Navy Operational Evaluation conducted by the Operational Test and Development Force of the Navy.

APL conducted Ship Qualification and Acceptance Trials of the 100-nautical-mile Talos system employing RIM-8C pulse homing and RIM-8D nuclear missiles on the newly commissioned USS *Little Rock* and USS *Oklahoma City* in 1960. APL also assisted the Operational Test and Development Force in a Technical Evaluation and Operational Investigation of the same system in *Galveston* in 1960 and 1961.

The first system to support the continuous wave homing, 100-nautical-mile-range missile was evaluated as a part of Ship Qualification and Acceptance Trials of the first nuclear-powered cruiser, USS *Long Beach*, in late 1961 and early 1962 (Fig. 2).

Development Assistance Tests for the introduction and evaluation of missile and shipboard system improvements were started in the early 1960's. That test program provided a realistic environment for the evaluation of missile, fire control, and weapon system improvements. It also provided a vehicle whereby development test work was conducted on board operational ships.

When an improvement or group of improvements was ready for evaluation, a Development Assist Project was proposed to the Navy's Talos System Manager, who would obtain Chief of Naval Operations approval and designate a project assignment. APL would prepare test plans for approval by the Navy, devise test procedures, and, with the assistance of the Operational Test and Evaluation Force, arrange for Talos ship services and any needed tracking aircraft, target aircraft, and surface and shore services. The services of missile and system contractors were provided by the U.S. Naval Missile System Engineering Station at Port Hueneme, Calif. The tests were performed under direction of an APL test conductor, with the very active participation of the Missile Engineering Station.

The primary categories of tests conducted as "Development Assistance Tests" were:

1. Prove-in of new capabilities such as countermeasures resistance, homing against surface

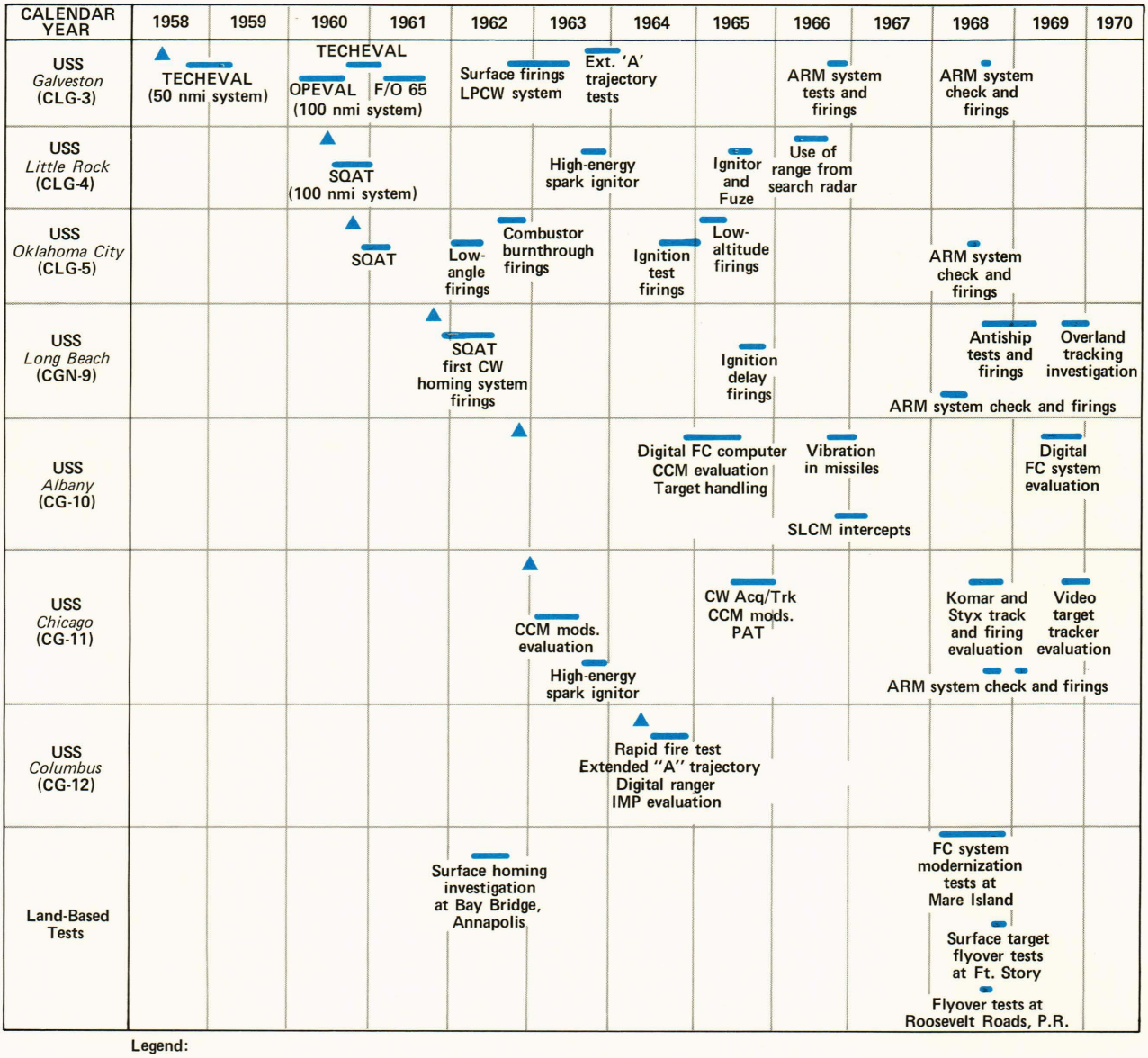


Figure 1 — Development Assistance Tests to evaluate missile and shipboard system improvements were conducted using operational ships. The types of evaluation tests and times involved are shown here.

targets, system coast provisions in case of temporary loss or fading of track, introduction of the digital fire control system, and introduction of antiradiation missile capability;

2. Demonstrations of missile capability against both low-altitude and high-altitude, high-speed targets and the ability of the system to sustain rapid-fire operations;
3. Prove-in of fire control system maintenance aids such as the Daily System Operability Test and the Integrated Maintenance Plan. Some tests and investigations required several project operation periods to be completed successfully, and were actively pursued for a number of years before completely satisfactory results were obtained.

A typical example of a Development Assist Project requiring several years of testing was the assessment of Talos capability against surface targets. The investigation of the technical problems started in 1962 with a series of land-based tests in which a Talos con-

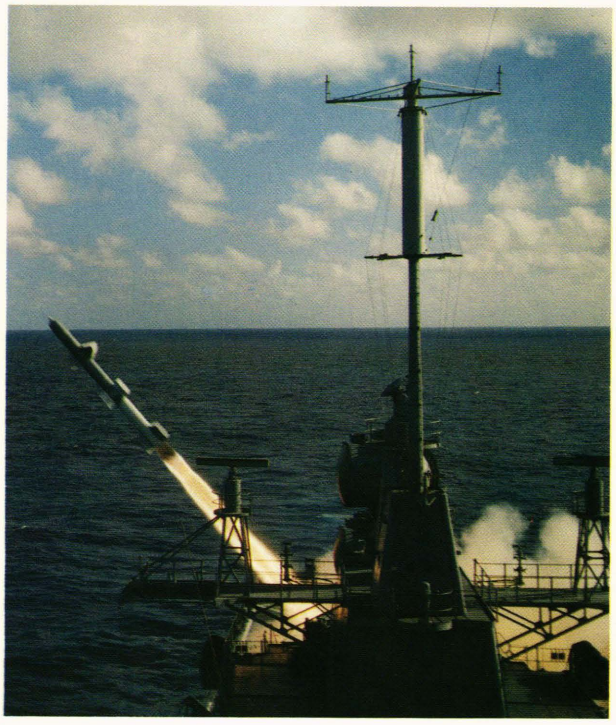


Figure 2 — Talos firing from USS *Long Beach* to evaluate the 100-nautical-mile missile and continuous wave homing system. Missile and weapon system evaluations were part of the *Long Beach* Ship Qualification and Acceptance Trials.

tinuous wave illuminator, a missile front end antenna and receiver assembly, and instrumentation to identify and record signal returns were installed on a pier of the Chesapeake Bay Bridge near Annapolis. The setup was used to gather radar reflection data on maritime traffic passing under the bridge, thus providing an evaluation of the capability of the Talos seeker to track the complex radar returns from ships. Following the Bay Bridge tests, missile firings from *Galveston* against a destroyer hulk were conducted in 1963 with considerable success, in terms of hits on the target and demonstration of extensive damage from missile impact, even though a warhead was not used. A problem revealed by these flight tests was a tendency of the missile seeker to lose track about 1 second before intercept because of the size and complexity of the target. A rapid shifting of the aimpoint along the length of the target caused considerable wing motion and erratic flight. A seeker modification in order to zero the wing control signal when this condition occurred was developed and tested aboard USS *Columbus* in 1964. Tests were also conducted with the Talos seeker mounted in the nose of a P-2V aircraft to evaluate receiver performance more extensively during antiship intercepts. The antiship test program culminated in 1968 with firings from *Long Beach* that demonstrated a Talos capability to intercept surface targets that varied in size from patrol boats to major warships.

The use of tactical ships as at-sea test sites for missile and weapon system development was very ambitious because test work had to be squeezed in between operational commitments. In spite of these heavy operational commitments, the necessary development and evaluation were accomplished and many valuable lessons were learned.

RADM WAYNE E. MEYER and CAPT RICHARD W. ANDERSON (Ret.)

OPERATIONAL LESSONS LEARNED

LESSON ONE

From its beginning, the Talos missile system was conceived as a long-range weapon system. Its propulsion method would have supported still more range than the guidance concepts on which it was based, and its time-to-target was respectably low. The range capability was double or triple that of contemporary naval surface-to-air systems. As the nature of air attack changed from gravity bomb delivery at relatively short range to air-to-surface missiles launched at considerable standoff, Talos promised the ability to reach the enemy's launch aircraft and their jamming support before their antiship missiles were launched. Talos' range capability would force the enemy to stand off to distances that would severely reduce the effectiveness of their antiship weapon delivery. We were proud of the technical achievements of the Talos missile system, but we learned quite vividly that missile systems do not stand alone.

The detection sensors upon which the Talos missile system depended were severely stressed to provide early enough designation to Talos fire control to permit missiles to reach their maximum range capability, especially in a jamming environment. Additionally, the Talos range capability made it a virtually unmanned interceptor, capable of operating in regions where aircraft alone held sway. This posed an additional problem for the search and surveillance components of the air defense system: it was not enough merely to detect approaching enemy aircraft, it was essential to know the movements of friendly aircraft and missiles in relation to each other as well as in relation to enemy aircraft. What we found was that, in general, the defensive system was not up to this requirement, and the problem was "solved" by not using Talos to its full capability, the air defense aircraft being favored due to its established position.

This disuse of long-range missilery, given the existing command and control situation, was probably as large a contributory factor to the demise of the Talos missile system as were the more often stated factors of electronic antiquation and maintenance expense. Had the capability been credible, the age and cost problems would have been solved. This problem of achieving really credible capability still plagues designers of antiair warfare weapon systems. Though weapons have changed, though newer and better sensors have appeared, though superior defensive aircraft have been designed, we still have the problem that good weapons systems are of true military value only if they can be coordinated with the entire ensemble. The secret of this coordination lies in the command and control system, its supporting sensors, its computational power, and its display and communications abilities to gain and make sense of the information about what is going on at great distances from the ships being defended. Talos history provided us with an early identification of a problem that will occupy and plague us for decades to come.

LESSON TWO

Looking back at our experience with the Talos missile system, we are reminded of a basic lesson that runs through all of its history, as well as the history of other missile programs: engineering changes are inevitable, and provisions must be made to accommodate them in an orderly manner. White Sands Missile Range was the only development and test facility nearer the sea than a laboratory bench, but much of the development testing needed to be done at sea. The Talos program never had an at-sea development site, except for the operational ships. That meant that the combatants had to squeeze development test work in with operational commitments. This way of life was acceptable in a programmatic sense only because the number of ships was so small that configuration changes could be kept track of and logistically supported to an acceptable degree. The ships accepted such constraints because it was the only way of getting capability improvements in a timely manner.

Today such methods are unacceptable. Ship classes are too large to be accommodated in such a fashion, and the technical personnel situation will not allow that sort of experimental activity. The lesson learned was that there had to be land-based test sites, combat system development sites, and program maintenance facilities where a much more orderly process of design and development testing could get things well in order before going to sea. The rigors of installation problems needed to be worked out before system components reached the recipient ship and where the details of computer programs could be put in order at relative leisure and without debilitating the ship's operational capability. Thus, we learned that it is not sufficient just to build ships and combat systems; rather, it is essential to consider carefully the need for a complete support system to accommodate orderly evolution of the weapon system.

ANNOTATED BUMBLEBEE INITIAL REPORT

In the first half of 1944, when World War II had not yet run its course, the technical focus of APL shifted from proximity fuzes and gun directors to guided missiles. To recall the events of nearly 40 years ago that set the stage for the development of the Talos antiaircraft guided missile (and of Terrier, Tartar, and Aegis, its offshoots), we reproduce the Bumblebee Initial Report that was issued soon after the assignment of a new task to APL in January 1945. The Annotations accompanying the report are intended to assist the reader in reconstructing the origins of a program that had a profound and lasting effect on the technical direction of APL. *Walter G. Berl*

THE JOHNS HOPKINS UNIVERSITY
APPLIED PHYSICS LABORATORY

SILVER SPRING, MD.

Operating Under a "Section T" Type of Contract
With the Bureau of Ordnance U. S. Navy

BUMBLEBEE
REPORT
No. 1
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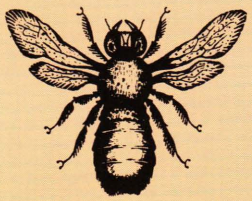
BUMBLEBEE

INITIAL REPORT



FEBRUARY
1945

Bumblebee_____
Report No._____
Copy No. _____

BUMBLEBEE INITIAL REPORT

As of February 15, 1945

Foreword

This is a statement covering the formulation and general planning of the "Bumblebee" program, as undertaken by the Johns Hopkins University Applied Physics Laboratory under a research contract of the Section T series with the Bureau of Ordnance, Navy Department. It provides an introduction to the activities associated with this problem, indicates the scope and background, and should serve to illuminate the series of progress reports on Bumblebee which will be issued at regular intervals.

The Applied Physics Laboratory, Johns Hopkins University, has acted for the past three years as a consulting technical group for the Research and Development Division of the Bureau of Ordnance, while operating as the Central Laboratory for Section T, Office of Scientific Research and Development. After December 1, 1944, the Laboratory continued its work under a new type of research contract directly with the Bureau of Ordnance, Navy Department. The primary emphasis in its technical program has been directed toward the protection of the Fleet against enemy aircraft. The VT fuze and the Mark 57 fire control system are specific developments to meet this particular military requirement. It has been recognized, however, that the nature of warfare is rapidly changing, and that while refinements can be introduced into fuzes and fire control systems, there is a growing possibility that the effectiveness of our present navy might be very seriously reduced by a large scale introduction of new types of enemy guided missiles during the late phases of this war. The use of the HS 293 and FX 1400 weapons by the enemy foreshadows advanced forms of aircraft attack against naval vessels for which inadequate protection will exist.

In July 1944, the Chief, Bureau of Ordnance requested an initial analysis and evaluation by Section T of the problem of protecting a task force against guided missiles launched from enemy mother-planes beyond the range of present fire control. Accordingly, with Dr. Bush's approval, a small group of Section T technical men explored this problem and submitted a report to Admiral Hussey and Dr. Bush.

It was the opinion of this group that some technical agency should give immediate and concentrated attention to the problem of developing a guided, jet-propelled, antiaircraft missile, preferably with supersonic speed, on a time scale which anticipates at least limited military use in the later stages of the present war.

This conclusion was reached as the result of consideration of a guided missile weighing 2000 pounds and traveling at a rate of 1850 ft. per sec. In this tentative design it was proposed that the missile would be launched to this velocity by means of rockets and driven to its target by a ram-jet motor. A payload of 600 lbs. of explosives was assumed. The auxiliary rocket-launching equipment would weigh an additional 2000 lbs., and would be dropped early in flight. A maximum flight time of 63 seconds would be required at an overtaking range of 38,800 yds. This was computed on the assumption that the misille would be fired at a target flying at an altitude of 10,000 yds. to intercept at a horizontal range of 20,000 yds.

It is of great military importance to the United States to learn whether guided, ram-jet missiles of supersonic speed are feasible as a weapon, since it would indicate what might be expected, for example, from the enemy in the way of surprise attacks on an invasion fleet. If an intensive effort were made by a suitable technical group, even a negative result would be valuable, in that it would provide evidence that no nation could bring such devices into effective use against us in a predictable length of time. 8

In December 1944, the Bureau of Ordnance was directed to proceed with the development of guided, jet-propelled antiaircraft missiles on an urgent basis, and the other Bureaus of the Navy were asked to give all possible support and assistance in carrying forward this program. The Bureau of Ordnance, recognizing the highly technical character of this problem, and cognizant of the fact that various aspects of the guided missile program are matters of prime concern and responsibility to several Government and Service groups, decided to handle this assignment in an unusual manner. The Chief of the Bureau proposed that this program should be made the overall responsibility of a contracting agency outside of the Navy Department, supported by Navy funds and with the responsibility for their activities accepted by the Bureau of Ordnance. This would allow freedom in the technical planning of the work, and would make possible a maximum degree of cooperation and joint participation in the program by other agencies in the general field of guided missiles. The former central laboratory of Section T now operates under a direct Bureau of Ordnance research contract; and the Chief of the Bureau therefore asked the trustees of the Johns Hopkins University to accept an assignment for the Applied Physics Laboratory to undertake a major program on jet-propelled antiaircraft missiles. At the end of December, the Johns Hopkins officials made a tentative decision to accept this assignment (Task F, code word "Bumblebee"), contingent upon being able to obtain additional technical personnel and facilities. 9

The Bureau of Ordnance and the Applied Physics Laboratory technical men recognized that cooperation and, wherever possible, joint acitivity with the agencies already interested in the general problem of guided missiles, is essential if effective results are to be obtained in a minimum time. Although this program was initiated and is supported by the Bureau of Ordnance, the work is of such broad scope and so closely allied to projects already under way in this country and in the United Kingdom that active cooperation with these other agencies is not only desirable, but necessary. This view was presented in letters from the Chief of the Bureau of Ordnance to the Army Air Forces, Army

Ordnance, National Advisory Committee for Aeronautics, the Office of Scientific Research and Development and the Navy Bureau of Aeronautics. All interested groups were asked to participate in the Bureau of Ordnance program with the Applied Physics Laboratory, and each was informed that its participation in the program would be given recognition. 10

The Applied Physics Laboratory will make every effort to work closely with all the technical agencies concerned, and with the various committees investigating the field of guided missiles, such as the Gilliland, Dewey, NACA, and other groups. It is recognized that the Applied Physics Laboratory, being a temporary war agency, is not expected to become a permanent central group 11
for guided missile work as a whole. However, if it can provide an effective technical arm in the immediate future by presenting an opportunity for detailed and continuous technical exchange in an active working laboratory located in close proximity to all of the Washington agencies, it should be of value to each group working in this field.

Representatives of the Laboratory have examined the literature available, and have been in touch with technical men in this country and abroad who are actively engaged in guided missile programs. Through OSRD channels, discussions were held directly with the G.A.P. Committee at two of its sessions in England. Informal liaison with associated technical agencies has been established, and more active collaboration is anticipated as the Applied Physics Laboratory technical program develops.

For several reasons the Applied Physics Laboratory, with the approval of the Bureau, has decided to limit the Bumblebee program to a jet-propelled AA missile of supersonic speed: in the initial phases of the work major emphasis will be given to ram-jets (athodyds), although an alternate based on liquid 12
rocket propulsion will be initiated as soon as personnel needs can be met. 13

During the first year (1945), the technical attack will be on the basic elements necessary to any guided supersonic missile, without major emphasis on a specific missile design. Empirical and laboratory investigations are already in progress, and it has been arranged for the Navy to survey and evaluate the situation at the end of the first year.

The basic problems to be determied are: (a) the thrust of a ram-jet versus the accompanying supersonic drag; (b) supersonice stability and control arrangements versus drag; (c) whether guidance at supersonic speeds presents basic difficulties or practical limitations not yet perceived. It is hoped that at least preliminary answers to these questions may be available by the end of a year of investigation (January 1946).

The Applied Physics Laboratory plans to add roughly three hundred people to the modest group now working on Bumblebee. In addition to maintaining a strong program at the Laboratory, the assistance of university and industrial groups on various technical phases of the problem is being arranged for under associated research contracts of the "Section T series" with the Bureau of Ordnance.

Expansion of the central laboratory space is now in progress; additional building facilities have been obtained at Forest Grove, Maryland, a short distance north of the present location in Silver Spring, which will accommodate the expanding needs of the Bumblebee Project, including a ram-jet laboratory. General administration of the Bumblebee Project will remain at the central laboratory.

The Bumblebee problem has been initially divided into several parts and assigned to groups working under technical supervisors as follows:

1. Burner: Fundamental problems of propulsion, involving stationary ram-jet experiments, thrust measurements, and fuels. Experiments will be performed simulating as nearly as feasible the conditions to be met in flight. This necessitates large blower and compressor facilities and the use of an open-circuit, supersonic wind tunnel, primarily for burner experiments.

2. Aerodynamics: The study of supersonic drag stability and control problems, and designs of wind tunnels and ducts. In the later stages it is expected that this group of necessity will also assume the overall design of the weapon. The facilities of the proposed supersonic wind tunnel will be used in some phases of this work, together with free-flight experiments.

3. Models: Primary emphasis on ram-jet thrust and drag by free-flight experiments at supersonic speeds. Measurements will be made on athodyd models in flight, using radio telemetering methods, together with radar and photographic tracking observations. This group will provide data to supplement the stationary burner experiments. Fuel injection, altitude controls, tracking and telemetering problems are among the secondary concerns of this group.

4. Guiding and Control Systems: Radar guidance, target tracking and gyro-servo systems for control and stabilization.

5. Facilities: Test fields and flight observing facilities, also experimental laboratory and large blower facilities.

6. Launching: This group has been organized to develop and study launching techniques.

In carrying forward a major program of the type indicated, it is planned to allocate specific areas of the problem to industrial and university groups, with several contractors invited to share with the Applied Physics Laboratory a sense of overall responsibility for the success of the program as a whole. The Applied Physics Laboratory expects to invite a major aircraft company to participate in solving the aerodynamic problems and the eventual design of the missile, and to assist with experiments using large blowers and the supersonic wind tunnel. A large industrial concern specializing in prime movers or heavy machinery will be asked to undertake a general program, including the design of a

complete weapon, but with a special emphasis on the ram-jet and propulsion problems. At least one organization specializing in fuels will be asked to accept a contract to develop various types of fuels, and to join in the ram-jet experiments.

A group at Princeton University has begun investigations of telemetering in cooperation with the Models group at the Applied Physics Laboratory.

At the University of Virginia, investigations have been initiated on the burning of fuels in a small-scale burner laboratory. Data from these experiments will be correlated with those obtained by the Burner group at its stationary burner laboratory in Forest Grove, and later with data from the large-scale burner work.

Since no facilities exist for full-scale ram-jet experiments, blower equipment, a power plant, and a facilities building are being provided at Daingerfield, Texas, through the Bureau of Ordnance. These facilities will provide 200,000 cfm at 30 lbs. per sq. in. (gage), and in addition, a high-pressure blower will be fabricated and installed which will convert the 30 psi gage output of one of the 100,000 cfm low-pressure blowers to 120 psi gage. The initial blowers will provide air for low-pressure (high altitude equivalent) ram-jet experiments and for the 24"x36" wind tunnel being designed by the Aerodynamics group. The series combination of the low-pressure and high-pressure blowers will provide air for high-pressure (sea-level equivalent) ram-jet experiments. A test field has been established at Island Beach, New Jersey, and a major test field in the western part of the country is proposed for later experiments.

It is hoped that this report presents a sufficient introductory picture of the interests, aims, and initial progress of the Bumblebee project. A monthly survey of progress will be sent regularly to persons on the present distribution list, and to a limited number of additional persons who may be specifically authorized by the Bureau of Ordnance to receive this information. Requests for Bumblebee reports should be addressed to the Supervisor of Technical Reports, Applied Physics Laboratory, Johns Hopkins University, 8621 Georgia Avenue, Silver Spring, Maryland.

ANNOTATIONS

1. In June 1940, the National Defense Research Council (NDRC) was established by the Council of National Defense, which, in turn, had been created in 1916 "for the coordination of industries and resources for the national security and welfare." In President Roosevelt's letter appointing Vannevar Bush, then the president of the Carnegie Institution of Washington, to be the chairman of this Committee, NDRC was directed to "supplement the activities carried out by the Army and the Navy by extending the research base and enlisting the aid of the scientists who can effectively contribute to the more rapid improvement of important devices, and by study to determine where new efforts on new instrumentalities may be usefully employed." The organization was designed to bring together civilians in universities and research establishments to work on projects that would be of value to the military services.

Its six divisions, subdivided into numerous sections, covered a wide spectrum of science and technology of concern to the Armed Services. In placing contracts, one factor was uppermost in the Committee's thoughts — the need for speed. Contracts were let, permitting key scientists to remain in their laboratories as far as possible. Exceptions, however, were made in such areas as antisubmarine warfare, radar, and rocketry, where large centers were established through contracts with universities. In rocketry, for example, the California Institute of Technology and George Washington University were pressed into service as contract managers.

This unusual, imaginative, and extraordinarily effective mobilization of scientists and engineers was expanded in 1941 into the Office of Scientific Research and Development (OSRD) with the additional functions of liaison with Allied governments and an Office of Field Service with the responsibility of transferring technical developments to the Armed Services and evaluating their effectiveness.

In August 1940, an NDRC contract was signed with Merle A. Tuve of the Department of Terrestrial Magnetism of the Carnegie Institution of Washing-

ton to develop a fuze that would explode an antiaircraft shell by radio signals reflected from a nearby target ("proximity" or "VT" (variable time) fuze). With the assistance of a small number of his colleagues (R. B. Roberts, H. H. Porter, and L. R. Hafstad), Tuve demonstrated in a few months of breadboarding and field testing that such a miniature radio system could be designed and could survive the acceleration of the projectile being shot out of a cannon.

Because of the great military potential of the device and the need to translate the concept speedily into a reliable weapon, Tuve's Section T (the initials of a Section frequently reflected the name of the Chief) was expanded from about 100 persons at the end of 1941 to 365 one year later. A contract was negotiated with The Johns Hopkins University on March 10, 1942, to organize an Applied Physics Laboratory to pursue the fuze work on an enlarged scale. Close relations with industry were established to oversee the design and production of the fuze's components and to improve the reliability of the device. A staff of more than 600 was assembled in the Silver Spring, Md., Laboratory complex in June 1944.

Development and production were telescoped in an intensive coordination effort. Within two years from the enunciation of the initial concept, a workable fuze was in production. Its first successful demonstration took place on January 5, 1943, during an engagement in the South Pacific between USS *Helena* and Japanese war planes.

2. The close ties established with the U.S. Navy Bureau of Ordnance during the development and funding of the VT fuze resulted in a shift in the relationship of Section T and OSRD. The Section T operating philosophy had moved toward the concept of a central laboratory that was responsible for the development of an idea to the demonstration stage, followed by its rapid transformation into production and introduction into service use. This could only be achieved by the early selection of industrial contractors and by close and continued liaison with the ultimate user. Untried in military procurement, except for the Manhattan Project, this broad concept went beyond the immediate charter of OSRD and led, in December 1944, to a formal separation. By then, the staff had grown to nearly 1000. The Bureau of Ordnance negotiated a contract directly with The Johns Hopkins University. However, this "Section T Type" contract retained most of the features evolved during the OSRD period and has been maintained with few changes to the present day.

3. The VT fuze and gun directors were intended primarily for Fleet use during the Pacific operations, where they had a profound impact on the defensive capabilities of ships against conventional air attacks. However, the fuze was equally effective against the V-1 attacks on England that began in July 1944, and as a countermeasure against the German offensive in the Battle of the Bulge in November 1944. While there was reluctance to use the fuze on land for fear the Germans might discover its principle of operation, the war's end was near enough to overcome that objection. In fact, the Germans had made independent efforts to design a proximity fuze of their own, but there was insufficient support and urgency to bring their development to a successful conclusion.

When the APL fuze project was technically completed in 1943, it permitted a switch to new projects. The development of guided antiaircraft missiles and their integration into an effective Fleet system became the major APL effort until the 1960's. New programs were then added on satellite navigation and submarine evaluation and security, as were projects in biomedical engineering and in the fields of energy, environment, and safety.

4. As ideas for a guided missile development program crystallized into action during the early months of 1944, questions were raised as to whether any major new project could be completed in time to play a decisive role in the war. By then, it was evident that the early successes of the Germans in western Europe and in Russia had been checked and had, in fact, been reversed. Britain remained unconquered. The near-disaster for the Germans, in their costly campaign in the Ukraine and entrapment at Stalingrad, had led to continued retreats to the prewar Polish frontier by the beginning of 1944.

Similarly, in the Pacific, the military situation had greatly improved. From Pearl Harbor until the Battle of Midway (June 1942), the war had gone incredibly well for the Japanese — better, in fact, than in their most optimistic forecasts. Within six months, they controlled a vast area stretching from the Aleutian Islands in the north to New Guinea in the south, and from the Indian border in the west to the Gilbert Islands in the east. The defeat at Midway (so aptly named) was the turning point. The Imperial Navy lost four aircraft carriers and never recovered from that blow, even though reconquests of strategic Pacific islands had to be paid for frequently at hideous costs.

The summer of 1944 saw the successful crossing of the Channel in Europe and the approaching invasion of the Philippines in the Pacific. In mid-October, the Battle of Leyte Gulf, one of the fiercest sea battles in history, commenced. The Japanese Second Fleet, containing Japan's main naval strength, was decimated. It marked the end of the Imperial Navy as an effective fighting force, opening the home islands to effective invasion for the first time since Kublai Khan.

5. Postwar surveys of German and Japanese developments in antiship and antiaircraft guided weapons indicated that neither country had pressed vigorously enough for them to be of value in their war efforts. Indeed, the Germans had a long lead from their early commitment to the development of liquid-fueled rockets that culminated with the V-2's

bombing of civilian targets in England and the Netherlands. After successful flight tests in 1941, 5000 V-2's were assembled, half of which reached English targets in the time from September 1944 to the German surrender in April 1945.

However, despite a many-pronged development effort in surface-to-air and air-to-surface missiles, not a single German system was pushed into production on a large enough scale to have a decisive impact. The air-launched HS 293, a 10-foot-long glide bomb propelled by a hydrogen-peroxide-powered rocket and flying at a speed of 500 miles per hour, was put into limited production in 1941 and was instrumental in sinking several British merchant ships in the Bay of Biscay. But later versions with radio-controlled guidance did not become operational. The FX 1400, also radio-controlled and flying faster than 600 miles per hour, arrived too late to be of value. A variety of liquid- or solid-fueled and rocket-propelled missiles reached flight test stage in 1944 but did not become effective antiaircraft weapons. Despite a lead time of four to six years over the Allies, the German program never played an effective role in the prosecution of the war.

The Japanese effort in the high technology of guided missilery was almost nonexistent. During the desperate Leyte Gulf engagement and on virtually one week's notice, the kamikaze attacks were organized in October 1944. Pilots would guide their planes into direct collision with ships in the expectation that the resulting fires and explosions would cause great damage. It is estimated that 5000 sorties were flown in this style. While three capital ships were sunk and 300 other vessels were damaged, the tactic was a failure from a practical point of view.

The Ohka ("Cherry Blossom") bomb, introduced into the Okinawa campaign in the spring of 1945, was even less effective. Slung under a conventional mother plane and accelerated by solid propellant rockets to a speed of 600 miles per hour, it, too, depended on human guidance. Not a single ship was sunk by this device.

6. In view of the limited German effort and the virtual absence of a corresponding Japanese development, it is incorrect to describe the Navy guided missile initiative in the summer of 1944 as a response to kamikaze or Ohka attacks, since neither of those weapons had yet been deployed. Rather, the decision to proceed arose from the fact that technologies had advanced to a point where such a development was, in principle, feasible. M. A. Tuve wrote in a letter to Vannevar Bush on July 19, 1944, about

> *...the new Navy tactical situation which may arise if the enemy adopts guided missiles for attack against task forces from airplanes just beyond the limited range of anti-aircraft for us.... We have thought about this problem for several years, and only in the last eight months have reluctantly concluded that we may have to face it during this war instead of the next one in view of the weapons already in use by the Axis powers and ourselves.... The problem must be faced before very long if we hope for real defense against future air attacks in this shrinking world.*

Information about Axis developments was sketchy and incomplete, at best. Not knowing the magnitude of the German effort, it was unavoidable that actions based on a "worst case" assessment had to be taken. Tuve wrote on November 30, 1944 in a memorandum to Bush and to Rear Admiral G. F. Hussey, Jr., Chief of the Bureau of Ordnance:

> *Various discussions in Section T during the first six months of 1944 indicated the probable necessity for attack on a 'chaser' problem in the immediate future, even if the probability of success were low, since the stakes involved are so large; if high-speed guided missiles are more feasible than has been expected and the enemy discovers this first, the risk for us is very great.*

The request by the Bureau of Ordnance for a formal proposal was, in essence, in response to ideas generated by APL on how to prevent attacks on ships by guided missiles launched from planes beyond the range of conventional antiaircraft guns.

The first APL concept, suggested in early 1944, was a subsonic pilotless "fighter-missile," referred to as Falcon. A more detailed analysis of the problem was undertaken in the summer of 1944. It was concluded that a subsonic chaser would only be marginally effective against a target that could take evasive action. A detailed proposal (largely based on analysis by Jesse Beams, professor of physics at the University of Virginia) specified a supersonic velocity (1850 feet/ second), a promising powerplant (ramjet), a convenient fuel (octane), and a warhead weight of 600 pounds. The small amount of available design data at supersonic velocities indicated that a reasonably compact structure should be adequate to carry this payload to a distance of 20,000 yards. Radar guidance and a homing device were suggested, as were solid-propellant boosters. The code name for the proposed device was Torch.

Early in 1945, the project acquired the code name Bumblebee. Years later, as individual missile types were developed, mostly mythological names starting with the Letter T, were assigned to them (Talos, Triton, Typhon, and Terrier).

7. None of the needed components (powerplant, radar guidance, or booster) existed at the time the overall design was formulated. While there was hope that proof of concept would be available within a year, no tactical missile was foreseen in less than five years. In view of the expectation that the war would end in 1945 or soon thereafter, the likelihood of a useful device before the war's end seemed remote.

In contrast to the VT fuze, which took less than two years from invention to production, the complete guided missile system required a much longer development time. Talos, the culmination of the 1944

Falcon proposal, entered the Fleet in 1958, while the shorter-range rocket-propelled Terrier missile (an offshoot of one of the Talos test vehicles) became operational in 1955. Fully effective antiaircraft systems are only now being introduced into the Fleet.

While the APL proposal was the most ambitious in its specifications (supersonic speed, radar guidance), several other programs were discussed and initiated at the same time. Little Joe, Wac Corporal, and Tiny Tim, all subsonic and rocket propelled, were pursued by different sponsoring agencies, as were radio-controlled air-to-surface bombs (Razon, Tazon, Roc, and Gargoyle). The National Advisory Committee for Aeronautics developed a subsonic, radar-guided air-to-surface missile (Bat).

8. In an October 24, 1944, memorandum to Captain C. L. Tyler, M. A. Tuve wrote:

> *Even a negative result of this kind should be extremely valuable, as the attack aspects of these devices are of at least as great significance as the chaser (defense) aspects. Results of either type are highly necessary for the United States to possess as soon as possible whether ready before the end of the war with Japan or not.*

9. In a memorandum on "Intensive Program on Guided, Jet-Propelled Antiaircraft Missiles," dated January 11, 1945, Rear Admiral G. F. Hussey, Jr., wrote:

> *On the basis of technical considerations and work already in progress, the Commander in Chief, United States Fleet, directed on 4 December 1944 that the Bureau of Ordnance program on the development of guided, jet-propelled antiaircraft missiles is to be carried forward on an urgent basis and further directed that other Bureaus and agencies of the Navy give all possible support and assistance to the Bureau of Ordnance in connection with this program.*

Admiral Ernest J. King, at the same time, instigated a comprehensive survey, by a committee chaired by Prof. E. R. Gilliland of MIT, of jet-propelled missiles and their continuing postwar implications. Its overall purpose was to review the status of such missiles, with particular emphasis on their future possibilities and thus to aid the Navy in shaping requirements for the weapons and for research in the fields related to their use. At Air Force Headquarters, a similar study was undertaken when the high-level Scientific Advisory Group was established under the direction of Theodor von Karman.

10. Representatives of the Air Force and the British Scientific Mission in Washington were assigned to APL as liaison officers.

11. The question of "permanence" was discussed with great intensity for several years following World War II. The relationship and responsibilities of The Johns Hopkins University, APL, its associate contractors, and the sponsoring government agency (Bureau of Ordnance), and the makeup and the technical goals of the Central Laboratory staff were debated at length. For several years, the future of APL as a stable, large research laboratory under Johns Hopkins sponsorship was in doubt.

12. Soon after the formal Task F assignment to APL for the development of an antiaircraft missile, it was realized that the technology could readily be extended to other end-uses as well. Studies were assigned within a year for the design of a long-range ship-to-shore missile (Triton). Task extensions for the development of antiradiation missiles and antiballistic missiles were formulated at a later date.

13. The liquid-fuel rocket alternatives were never seriously considered. However, test vehicles propelled by solid propellants proved sufficiently adaptable to short-range applications that a separate program — Terrier — was organized to exploit the technology. Terrier became a dominant shipboard missile system.